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RUSSIAN APPROACH TO TERRAIN-VEHICLE SYSTEMS

(An Exercise in Pragmatism and Continuity)

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FINAL REPORT

By

M. G. Bekker

Under

Contract No. DAHC19-70-C-0019

DA Project No. (2M061102B52B)

U.S. ARMY RESEARCH OFFICE

Arlington, Va.

Delco Electronics

General Motors Corporation
- Santa Barbara Operations
Santa Barbara, California

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13. ABSTRACT

Dr. Bekker reports on his in-depth study of the evolution of Russian research on terrain-vehicle systems. After reviewing some 3000 references to literature on the subject in the past 35 years, he selected about 450 books and papers (see bibliography) for further study. He traces the evolution of Russian work, analyzes the methods and results, and discusses the influence that research in other countries had on these Russian efforts. He informs the reader of the current status of Russian research in this field, and compares it with the status of U.S. research. Dr. Bekker concludes that "though plagued with inefficiencies and frustrations," the Russians have evolved a pragmatic approach to research in terrain-vehicle systems that is exemplary for its "persistent and dynamic continuity."

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FOREWORD

During the past decade, American research on terrain-vehicle relationship was criticized on the grounds that the returns were not commensurate with the investment. Although particulars were never voiced publicly, with minor exceptions of papers by Headley (1962), AIA (1962), and Bekker (1963, 1964, 1970), the facts appear to have exposed a problem: major programs were cancelled before completion, support and funding were reduced, and the interest waned to such an extent that a number of experienced workers found jobs elsewhere.

The total investment in "ground mobility" research during the past 20 years amounted to several million dollars. Though the sum may be negligible by comparison to the cost of projects in other fields that were also criticized, a professional study of methods and techniques used in this particular field could in the future help by removing grounds for a similar criticism. And, not unlike other cases, such a study might help to redirect the effort toward a more effective avenue of progress.

It was with this thought in mind that late in 1968 I approached Dr. Richard A. Weiss and the late Dr. Leonard S. Wilson, and suggested that we compare our approach with that of others to see what might be learned - assuming the future is still open to effective studies of TERRAIN-VEHICLE SYSTEMS. A proposal was prepared, reviewed by groups of experts, and approved in 1970.

Since among the countries that conduct work on off-road locomotion, Russia seemed to be leading, at least quantitatively if not qualitatively, it was agreed that an analysis of the Russian state of the art in the discussed area would be the primary objective of my study. Other countries were to be included on a need-to-evaluate basis.

The analysis and conclusions presented in this volume are based on the open Russian literature pertaining to the following professional activities: automotive engineering, agricultural soil-machine technology, and specialized soil-machine studies related to earth moving, to traversing organic "soil" (turf) and to special locomotion (lunar, geological exploration, etc.). References pertaining to other related fields of activity

also were used as specified in the test. Russian soil mechanics "per se" proved to be irrelevant.

The backbone of the proposal and the performing of this study was my library which contains some 5000 entries that were collected over 20 years. In addition, the Library of Congress and the Harvard University library were the source of important information. However, the most valuable and most recent references were obtained from the collection of the National Tillage Machinery Laboratory, Department of Agriculture. This unique collection of Russian publications is the personal accomplishment of the Director of the Laboratory, Dr. W. R. Gill. Without his help and cooperation, significant literature in several critical areas would not have been available to this writer for an in-depth analysis.

Prior to and shortly after the initiation of this work I perused about 3000 references covering the period 1935 to 1970. From these, approximately 450 references were selected for further study; they included approximately 107 books and some 343 papers, as recorded in the Bibliography to this report, with a tolerance allowable for quotes "after someone else's quotes."

The literature sample assembled in the Bibliography appears to be quite representative of the methodology and the school of thought, including much technical detail.* This I deduced from the review of the approximately 1700 publications that were either not quite relevant to, or repetitive of, concepts and ideas presented in the selected 450 references.

The variety of intermingling topics, frequent difficulties in defining the crucial points, and, in general, the confusing Russian referencing and symbol using, created problems which had to be resolved right at the onset.

* This report also includes its share of technical detail. The casual reader who is not interested in such detail is advised to scan such material to capture the between-lines comparative reason[illegible] to read Chapter VII carefully starting with "Summation".

In order to see through the maze of different denotations – often for the same value or equations – and to dissect the topics frequently interwoven in one paper, I introduced the new, uniform symbols listed in the Symbol Index, and divided the main topics into groups that later became the titles for Chapters II through VI of this volume. Since the separation of topics was sometimes difficult, or could have been arbitrary, some repetition became unavoidable.

The tracing of influences of American work upon the Russian, and vice versa, requires knowledge of both. Therefore, this report includes fragmentary accounts of U.S. activities and pertinent references to help clarify a comparison of both approaches. The fact that Russian publications referenced specific U.S. work was very helpful in following the logic the Russians use in their approach. These references usually defined the research areas and quoted the names of Americans and several other foreign workers whose contributions, as one may assume, were at least of interest to the Russian researchers. In a number of cases, however, no U.S. or other references were given, though it was clear that the topic or idea was not of Russian origin.

The titles of Chapters II through VI indicate the evolutionary character of Russian research in off-road locomotion. Although many activities were conducted simultaneously, an initial preoccupation with a soil-value system is evident (Chapter I). However, the need for a study of the soil-value "per se" did not emerge until much later (Chapter VI). Chapters II, III, and IV dramatize the importance of the solution of this problem, as well as the amount of effort spent by Russian researchers to define what and how to measure in the ground, in order to optimize the parameters of design and performance in locomotion, tillage, ploughing, and earthmoving. *

The realization that without measuring, no predictive evaluations can be made is implicit in the colorful variety of mathematical modelling of soil-vehicle interface (Chapter V). This realization gradually pushed the researcher toward analyzing larger and larger machine-environment-mission complexes, which unavoidably led to terrain-vehicle system optimization (Chapter VI).

* In the present study, locomotion was the prime objective.

The influence of Amercian work performed between 1954 and 1960 at the Land Locomotion Laboratory in Detroit should not be underestimated. It was this work which seems to have spurred much thinking in Russia, and in all probability spirited new activities (Chapter VI).

The story, as told, unveils the sober, pragmatic Russian approach, which though plagued with inefficiencies and frustrations, seems to have displayed in its evolution, persistent and dynamic continuity — a remarkable feat in this age of technological discontent.

May 25, 1971 MGB

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CHAPTER I
RESEARCH CLIMATE AND ENVIRONMENT

Introduction

Evaluation of the organization and policies guiding Russian R&D was not the objective of this study, since the latter had been devoted solely to an analysis of engineering and scientific problems related to terrain-vehicle interface.

However, as it may be often difficult to see the subject matter in a proper perspective, without an insight into the climate and the environment surrounding Russian workers in off-road locomotion, a brief search was made beyond the technological literature on soil-vehicle relationship.

Difficulty was encountered in this effort because of the lack of material pertaining specifically to ground locomotion. Fortunately, the automotive and agricultural literature which included soil-vehicle relationship was available. Since this literature was often concerned with the organizational and policy problems, it was sufficient to read between the lines in order to attempt the sketching of the R&D background as it gradually emerged.

This Chapter reports the highlights of findings and opinions which are discussed later in more detail in this volume. It also touches upon the Russian philosophy of R&D, policymaking, and the organization of research.

Theory vs Empiricism

Most of the students of Russian R&D agree that research has a very strong – perhaps too strong – position in the national effort (Kozlowski, 1969). This situation is examplified by a great emphasis upon the theory and generalization:

> "... who thinks empirically and who negates the role of theoretical generalization, thus naturally confines himself to the niveau... at which he himself stands, and is incapable of seeing more remote perspectives... He is like a mole which can see only what is in front of his nose" (Kedrov, 1963).

Words of this kind though published recently by a noted philosopher were not new. As it will be seen in this volume, they reverberated in the studies of ground locomotion mechanics from the time of Letoshnev (1936) and Goriachkin (1937), to the era of Guskov (1966) and Ul'yanov (1969). But this seemingly obsessive theorizing and generalizing must favorably impress every student of Russian work, even if he disagrees with the outcome of the theory. For the theories developed are rarely abstract and academic; in a great majority they concentrate on selected practical topics, seldom go beyond tangible boundaries of generalization, and always focus on a neat package of a complete problem and its solution, for practical purposes. The textbooks and papers listed in the bibliography speak for themselves in that respect.

The restraint in the "scientification" of practical engineering has been achieved by the Russian researchers through the mixing of theory with experiment.

> "Contemporary experimental studies on soil-working mechanics depend to a large extent on scientific-engineering foundation. When formulating tasks of broader scientific nature, it is necessary however, to SIMULTANEOUSLY WIDEN THE BASIS FOR LABORATORY AND ENGINEERING WORK" ("Voprosy..." Vol VII, 1961), since this is the only logical road to progress, *)

was the theory of what this writer calls the "Minsk School of Thought", and of other influencial organizations. The cycle: theory → experiment → better theory, can be seen in many publications listed in the references to this volume, and in the Russian accomplishments of the past 35 years.

It is believed that the high regard for a theory without abandoning its empirical validation, and the sharp focussing of work on a practical end-product, are the mainsprings of the Russian success.

There are few if any who would question the rationale of such an approach. Yet, surprisingly as it may be, some of the American research in off-road locomotion took a different course, which will be shown in more detail later in this volume, in a

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* Capital letters added.

comparison of U. S. and U. S. S. R. work. On the background of that comparison, it may become clear why the Russians abstain from the American over-generalized, push-button computarization and scientific sophistry, on one hand, and why on the other,

> "Russian methodologists scoff at the American brute force technique of trying all ideas sensible or not... and reject the German concept of struggling for the simple best solution with the test tube over slide rule rather than giving a trial in the field to a whole variety of promising ideas. The Russians believe in a happy medium between the extremes of American empiricism and German trial-by-theory" (Mechanical Engineering, 1970).

Men, their Publications and Work

Theorizing and generalizing, in a climate heated by Kedrov's words and moderated by the pronouncements of the "Voprosy..." is a contagious thing, for it represents the most accessible rostrum for individual enhancement of professional status. No wonder that it has attracted prominent workers, often of the highest caliber.

It is most doubtful that any other country has surpassed Russia in quality and quantity of Academicians, scholars, professors, and engineers employed directly or indirectly, permanently or temporarily, in soil-machine relationship and off-road locomotion, during the past 35 years. In any case, no one, including the U. S. A, has surpassed the number of publications in that area.

This conclusion reached by this writer some time ago has been recently corroborated by an astute researcher in soil-machine systems, and expert in agricultural science and technology; after spending three months in Russia he noted that "research material published in U. S. S. R. exceeds that in U. S. " (Gill, 1970).

Perusal of Russian literature also shows, at the first glance, that not only the quantity is large, but also the quality is high. This outcome should be of no surprise, considering the very high caliber of professionals involved. A closer look upon this situation and its consequences will be taken throughout the pages of this volume, and in Chapter VI, in particular.

Publications in soil-machine relationship are, naturally, State financed. The fact that they appear under the auspices of prestigious (local Republic) Academies of Sciences, including, sometimes, the U. S. S. R. Academy of Sciences, or other influencial Research Institutes or Ministries, helps to attract good workers, to establish a school or schools of thought, and to provide intellectual leadership based more on recognition of achievement, and less on politics – though the latter still play their role.

A similar situation exists perhaps, in Germany, England, Japan, Sweden, and Italy. It exists in Poland, Romania, East Germany, and Czechoslovakia. However, the U. S.-performed research in off-road locomotion does not appear to have contributed to the establishing of intellectual leadership on a national scale, as will be discussed later in this volume.

Altough Russian researchers are strict pragmaticists, in contrast to what we have witnessed in America, their sprawling bureaucracy, the multitude of research organizations, and the apparent lack of communication and of modern managerial techniques (as discussed in Chapter VI) seem to have seriously threatened the research output.

It is this writer's opinion that both the quality and quantity of work, mentioned before, could not have existed under the prevailing system, if it were not for the leadership of a few individuals and a few institutions which, though competing, succeeded in establishing a school of thought compatible with modern concepts of engineering.

The leadership indisputably belongs to Russian automotive and those agricultural engineers who are concerned with tractors and special vehicles. Geographers, geologists, environmental scientists, experts in soil mechanics, and civil engineers had relatively little to say, as the perusal of technical literature indicates.

The subsequent pages and index to this work are quite convincing that the problems are of an automotive engineering nature, and that the task of their solution was assigned to the right people.

Institutes and Institutions

Research work is performed occasionally at the factories, invariably at special R&D Institutes, and often at the universities. The description and evaluation of the Institutes

reported here were mainly based on information from Berliner (1969), Kozlowski (1969), Gill (1970), and to a certain extent from the somewhat outdated brochure "Farm Mechanization in the Soviet Union" (1959). In addition, other references were used as specifically quoted in the text.

The present analysis of institutions involved in ground locomotion and soil-machine research did not go beyond the institute-factor-university level, as detailed material was not readily available, and a broader study would require much additional effort, well beyond the scope of the present work.

Thus, while relatively little is known to this writer about the organization of research among the various Ministries, councils, committees, and industries, the role of Research and Development Institutes became fairly clear from the study of technical literature.

The term R&D in Russia covers "basic" research, applied or exploratory engineering research, and experimental work, up to and including the construction of the first prototype, its testing, and monitoring the first output of the production line. Theory, experiment, and design intermingle in the complete cycle of product birth and life, until the production is well established.

Rapid progress in, and the modernization of, production methods apparently necessitated loosening of some rather unwieldy science policies. In 1961, the State Committee for the Coordination of Scientific Research was established. The committee shares its coordinating powers with State Planning Committee, GOSPI AN. The top level control of the Party on R&D is exercised by the Departments of Science and Education of the Central Committee, which is often mentioned in the editorials and general articles published in the technical literature.

Much of early R&D – particularly high priority R&D – is conducted by various Ministries through their Research Institutes, as can be seen from the sponsorship of technical publications. Local Republics and the U. S. S. R. Akademies of Sciences also are responsible for fundamental and some applied Research.

The chief current criticism of the system is that too much manpower and resources are spent on research and not enough on development. The ratio of monies spent on basic research by U. S. S. R. and U. S. after 1960 was believed to be as follows: U. S. S. R., 20%; U. S. A., 9%, (1968 data for U. S.). Knowledgeable Russian officials point out that this imbalance must be, will be, and is being corrected (Kozlowski, 1969).

Review of the leading Russian and American literature reported in detail in Chapter VI shows that in automotive and soil-machine technology the percentages of articles published on such topics as Mathematical Modelling (MM) and design, engineering, and testing (DE&T) are practically equal:

	MM	DE&T	Other
U. S. S. R.	27.8	41.3	30.9
U. S. A.	24.0	44.0	32.0

However, numerically respective, U. S. publications are below Russian publications as the numbers of analyzed topics show:

	MM	DE&T	Other
U. S. S. R.	84	125	94
U. S. A.	48	88	64

Other criticisms of Russian R&D Institutes pertain to the imbalance in research-technician manpower ratio and chiefly in the lack of facilities. The latter could be noted easily when studying the literature on soil-machine relationship. The test equipment was crude, and the lack of computers was evident in endless nomograms. Gill (1970) reported, however, that these deficiencies are being eliminated at a fast pace, and a special high level committee was organized to cope with the problem.

This observation coincides with Kozlowski's (1969) comment that "since 1966 there has been a subtle-but-significant shift to eliminate existing problems in Soviet R&D."
The same conclusions were reached by Berliner (1969). Nikitin (1967) also wrote about forthcoming changes in the structure, organization, and specialization of automotive production.

There were reportedly 2019 Institutes in U. S. S. R. in 1964, most of them responsible to the particular Ministries. Two of these, The Automotive R&D Institute (NAMI) and

Central R&D Institute for Mechanization and Electrification of Agriculture (TsNIMESH), seem to occupy the leading spot in automotive off-road locomotion and soil-machine technology. The first reports to the Ministry of Automotive Industry, while the second to the Belorussian Ministry of Agriculture and Belorussian Akademy of Sciences. The third Institute, which seems to play an important role in problems analyzed in this volume, is the Federal R&D Institute for Agricultural Machinery, named after Goryachkin (VISkHOM). Many others, which were reported to have a connection with works enumerated in the bibliography to this volume, are listed in the next chapter.

The plurality of organizations involved appears to be staggering, and the maintaining of liaison, beyond control. And it must be so, since each Institute is specifically responsible for dissemination of information. In addition, some of the Ministries attempt to resolve these problems.

The organization, staffing, and budget of the new Information Service of the Ministry of Automotive Industry appear to underscore rather dramitically the severity of the problem. The mission of the Service is to:

> "safeguard the thoroughness and completeness in gathering and dissemination of scientific-technical information related to various pertinent fields of activity in the U. S. S. R. and abroad," (Fedoseeva, 1967).

The prestige of NAMI is of long standing. In 1968, that institution celebrated its 50th anniversary. Its long history and accomplishments have been described on this occasion in a series of articles (Khlebnikov and Osipyan, 1968, Naidenov et al., 1968; Strokin, 1968), and are very impressive.

A year before, in 1967, the tractor and agricultural machinery industry celebrated its golden anniversary. That industry was originally dependent on work performed by the former R&D Institute for Tractors and Automobiles (NATI), which was merged with NAMI in 1946. A paper by Sinitsyn (1967) complements, in a sense, the information about NATI - NAMI activities reported by Khlebnikov, Naidenov, and Strokin.

Besides the description of technical goals and achievements, much emphasis is put in these articles on:

- close cooperation with the industry
- development of new automotive technologies
- system (operational) analysis of domestic and foreign progress (which was considered to be very helpful in the selection of Italian Fiat for mass production in the U. S. S. R.)
- electronic data processing and computerization
- increase of vehicle reliability
- economy and reduction of the exploitation of natural resources standardization
- research and development in new 1975 to 1980 vehicle types
- development of automotive technology for the North and North East
- increase of maintainability
- development of servo mechanisms
- human engineering.

Other Institutes follow more or less the same path leading to the same goals, as circumscribed by their specific mission. Thus while NAMI has a broad interest in all the automotive equipment, the TsNIMESH and VISkHOM extend their activity into ploughing and tillage machinery, while limiting their interest to the agricultural tractors and special purpose vehicles (Mekhanizatsia i elektrifikatsia selskogo khoziaistva, 1968; Issledovanie rabochykh organov pochvoobrabatyvayushchykh mashin, 1967).

Little, if anything is known about staffing and internal organization of the Institutes. Around 1921 NAMI counted 86 workers; in 1926, 177 workers (Khlebnikov and Osipyan, 1968).

Today the number probably goes into thousands. At the Federal Institute for Farm Mechanization (VIM) there are 600 people. Several are Ph D's or University professors; 80 have MS degrees. Technicians and auxiliaries include 400 workers (Gill 1970). This would indicate that the balance of manpower in this research is close to that in the United States, in a similar organization.

The structure of a day's work in such an institute quoted after Pochekhanov (1969) is as follows:

Scientific work	61.5%
Administration	9.6
Unskilled work	8.6
Literature Search	5.8
Waiting, non productive work	5.8
Study, learning	
Social work	4.8

The time provided for social work indicates the nature of motivation of research. The reported introduction of work incentives similar to those used in the U. S. A. will probably not change these figures much, although such incentives may be most beneficial in other areas of R&D cycle and production.

Multitude of Efforts and Geography

As indicated in the preceding lines, the interest in soil-machine relationship and technology is widespread. In general, it appears to follow all the climatic, geographical, and geological regions, which may be deduced from the location of particular Institutes. Some of the Institutes are limited to specific territories such as "non-chernozem" soil zone (Minsk center). The others are of more general character.

While it is extremely difficult, if possible at all, to list the organizations and institutions involved, and to determine the amount of effort they allocate to the discussed area, it was thought that the listing of instituions, based on the affiliation with and/or sponsorship of authors reviewed or referred to in this work, will give a fair measure of the number of institutions involved. The first-order approximation as to who does most of the work may be judged if the frequency of particular quotations appearing in this volume, and in the references, is considered; NAMI and TsNIMESH undoubtedly will lead a long list of the others:

- Akademiya Nauk SSR (Academy of Sciences SSR)
- Akademiya SHN im. Lenina (Lenin Academy of Agricultural Sciences)
- Akademiya Nauk ARM SSR (Armenian Academy of Sciences)
- Beloruskii Politekhnicheski Institut (Bolorussian Inst. of Tech)

- Bashkirskii SHI (Bashkir Agricultural Institute)
- Chelabinskii IMESH (Chelabinsk Inst. for Mech. & Electrific. of Agriculture)
- Dnepropetrovskii Inzhenerno - Stroitelnyi Institut (Denpropertrovsk Design and Engineering Institute)
- Frunzenskii Politekhnicheskii Institut (Politechnik Institute, named after Frunze)
- Gorkovskii SHI (Gorkov Agricultural Institute)
- Gosudarstvennyi Komitet Po Avtomatizatscii i Mashinostroenii (Govt. Committee for Automation and Machine Des.)
- Gorkovskii Politekhnicheskii Institut (Gorkov Inst of Tech)
- KADI (Kiev Motor Ways Institute)
- Kaukasskii Politekhnicheskii Institut (Caucasian Inst. of Tech)
- Kharkovskii Avtomobilno-Dorozhnyi Institut (Kharkov Institute for Motorways)
- Kubanskii SHI (Kuban Agricultural Institute)
- Kuibyshevskii SHI (Kuibyshev Agricultural Institute)
- Krasnoiarskii SHI (Krasnoyar Agricultural Institute)
- Institut Mashinostroeniya AN BSSR (Machine Design Institute Acad. of Sc. Bieloruss. SSR)
- Institut Gornego Dela (Institute of Mining)
- INSTorf (Research Institute for Turf Industry)
- Lvorvskii Avtobusny Izavod (Lvov Coach Works)
- Lvovskii Politekhnicheskii Institut (Lvov Inst. of Tech)
- Lvovskii Lesotekhnicheskii Instut (Lvov Forestry Institute)
- Leningradskii Inzhenerno-Stroitelingi Institut (Leningrad Design and Engineering Institute)
- Leningradskii SHI (Leningrad Agricultural Institute)
- Ministerstvo Avtomobilnoi Promyshlennosti SSR (Ministry of Automotive Industry of the SSSR)
- Moskovskii Avtomekhanicheskii Institut, MAMI (Moscow Automobile Institute)
- Moskovskii Inzhenerno-Stroitelnyi Institut (Moscow Design and Engineering Institute)
- Moskovskii Avtozavod im. Likhacheva (Moscow Automobile Works, named after Likhachev)

- Moskovskii Avtomobilno-Dorozhnyi Institut, MADI (Moscow Institute for Motorways)
- Moskovskoe Vyshe Tekhnicheskoe Uchilischche in Baumana, MVTU (Moscow Technical College, named after Bauman)
- Minrsterstwo SH SSSR (Ministry of Agriculture of SSSR)
- Mytishinskii Mashinostroitelnyi Zavod (Mytishin Machine Works)
- Minskii Avtozavod (Minsk Automobile Works)
- Nauczno Issleodovateiskii Institut Shinnoi Promyshlennosti NIISHP (R&D Institute for Tire Industry)
- Minskii Traktornyi Zavol (Minsk Tractor Works)
- Nauchno-Issledovatelskii Institut Avtomobilnogo Transporta, NIIAT (R&D Institute for Automotive Transport)
- Nauchno Issledovatelskii Avtomobilnyi i Avtomotornyi Institut, NAMI (Automobile and Motor R&D Institute)
- Nauchno Issledoratelskii Avtotraktornyi Institut NATI (Automobile and Tractor R&D Institute)
- Odesskii Automobilnyi i Traktornyi Nauchno Issledovatelskii Institut (Odessa Tractor and Automobile R&D Institute)
- Rostovskii Inzhenerno-Stroitelnyi Institut (Rostov Design and Engineering Institute)
- Stalingradskii Mekhanicheskii Institut (Stalingrad Mechanical Insuitute)
- SibMIs (Siberian... ?)
- Sibirskii Avtomobilno-Dorozhnyi Institut (Syberian Motor Ways Institute)
- Tsentralnyi Nauchno Issledovatelskii Institut Mekhanizatsii i Elektrifikatsii Selskoyo Khozyaistva, TsNIIMESKh, ASHN BSSR (Central R&D Institute for Mechanization and Electrification of Agriculture. Academy of Agricultural Sciences, Belorussian SSR)
- TsNITA (?)
- Timiryazev Sel'skokhozyainaya Akad. (Timiriazev Agricultural Academy)
- Tsentralnyi Nauchno Issledovatelskii Institut Mekhanizatsii Energetiki Lesnoi Promyshlennosti (Central R&D Institute for Mechanization and Energy Exploitation of Forest Industries)
- Tsentralnyi Nauchno Issledovatelskii Institut Mekhanizatsii i Elektrifikatsii TsNIIME (Central R&D Institute for Mechanization and Electrification)

- Ukrainskii Nauchno Issledovatelskii Instiʻut Mekhanizatsii Sel'skogo Khozyaistva (Ukrainian R&D Institute for Mechanization of Agriculture)
- Voronezhskii SHI (Voronez Institute for Agriculture)
- Vsesoyuznyi Nauchno Issledovatelskii Institut SHmashin im. Goryachkina, VISHOM (Federal R&D Institute for Agricultural Machinery, named after Goryachkina)
- Vsesoyuznyi Institut Mekhanizatsii VIMe (Federal Institute of Mechanization)
- VNIIStroidormash (Federal Institute for Road Building Machinery)
- VIKA (Military Engineering Akademmy named after Kuibyshev?)
- Vsesoyuznyi Nauchno Issledovatelskii i Konstruktorsko-Tekhnicheskii Institut Azbestovykh Teknicheskikh Izdelii (Federal R&D Institute for Design and Technology of Asbestos Material)
- Vsesoyuzny i Institut Mekhanizatsii i Elektrizatsii Sel'skogo Khozyaistva VIMESH (Federal Institute for Mechanization and Electrification of Agriculture)
- Vladimirskii Traktornyi Zavod (Vladimir Tractor Works)
- Yaroslavskii Shinnyi Zavod (Yaroslav Tire Works)
- Zaporozhskii Mashinostroitelnyi Institut im. Chubarya (Zaporoгozh Machine Design Institute named after Chubar')

The above list is by no means comprehensive as it does not include organizations which may perform proprietary and/or classified work. It also is not known who specifically did R&D on the Russian Lunar Roving Vehicle, the "LUNOKHOD," and who studies lunar terrain from a locomotion viewpoint. In the U. S., NASA spent a great effort in this area.

In a sense, however, the Russians already have a land "locomotion institute" right on the moon, for the Lunokhod is equipped with a soil penetrometer and the "9th" wheel probe. The latter provides information for vehicle designers, while the first satisfies the requirements of geologists and soil physicists (Pravda, 1971). NASA has a rather long way to go before these achievements are matched. In this respect the Russion interest in soils and machines follows not only the GEO-, but also the "LUNO-graphy," while ours is lagging.

With the strong drive to expansion and generalization, and with a sober engineering approach based on scientific premise cultivated in a difficult organizational but favorable intellectual environment, the Russian work on soils and machines is very impressive, as will be discussed later.

CHAPTER II
PHYSICAL SOIL VALUES AND PARAMETERS

Introduction

Science does not necessarily precede technology. In the old days, in particular, the reverse was true: ships and planes were built long before the discovery of laws of fluid and gas dynamics; and off-road locomotion has been no exception. Even more, off-road locomotion is one of the best examples of technology built predominantly, if not solely, on empirics, without much scientific insight.

Under these circumstances it would be surprising to expect that early Russian efforts took a very scientific course of action in design of agricultural tractors and off-the-road vehicles. The pressure in reconstruction of the post-revolution ravages necessitated the full use of technological know-how already available in the West, rather than a fresh original start based on theoretical premises. Thus the student of Russian technology of that era finds the followers, rather than the innovators, for whom adaptation and modification of existing material was preponderant over the creation of the new one.

Such an attitude, however, did not prevent some Russian workers in off-road locomotion to search for more theoretical solutions, even though those of a purely empirical nature were readily available.

Bernstein-Letoshnev Era

In March 1913 Rudolph Bernstein in Germany wrote a paper entitled "Problems of Experimental Mechanics of Motor Ploughs." The title was somewhat misleading, for the article dealt largely with soil deformation under the action of rigid wheels, and produced the first general concepts of soil parameters for off-road locomotion, rather than for ploughing.

World War I, and the introduction of pneumatic tires in agricultural tractors in the late twenties, were not conducive to the elaboration of Bernstein's system of soil values. Thus between the two World Wars very little, if anything, was heard about

his work. Even such a prolific American writer and diligent student of the problem as McKibben et al. (1939; 1940) used not only qualitative soil values defined in loose terms of "blue grass pasture," "fall-plowed loam," or "settled title loam," but also used arbitrary, descriptive civil engineering soil "values" such as liquid limit, plastic limit, plasticity index, etc., which can never be correlated with quantitative values of locomotion (McKibben and Green, 1940).

Before that time, however, a Moscow University Professor, Letoshnev (1936), performed extensive studies and experimental verification of Bernstein's theory and published the results in a voluminous collective treatise on the theory and construction of agricultural machinery.

Sociological studies of the impact of science upon technology indicate that the time lag between the first formulation of a theory and its practical utilization is seldom shorter than 10 to 20 years. Letoshnev's work was no exception; its effect, although immediate, started gaining momentum in Russia only in the fifties and early sixties, while in other countries it was virtually unknown until the late fifties, when it was first published in the United States (Bekker, 1956).

Letoshnev, however, did not invent an entirely new soil value system. He followed the long line of thought by Morin, Grandvoinet, Gerstner, Schultz, Meyer, and Bernstein and concluded that "in order to solve in a first approximation" a number of problems such as prediction of wheel diameter and width, in terms of quantitative parameters which empirically characterize soil properties, it was necessary to adopt a rule which is followed by the soils in load-deformation process. He noted the difficulties encountered by his predecessors in obtaining experimentally verifiable solutions, and pointed the original erroneous assumption that unit soil load p increased with depth z in accordance with the rule:

$$p = a_1 z + a_2 z^2 \tag{1}$$

where a_1 and a_2 were empirical coefficients. Since experiments by Meyer and Bernstein (1913) also showed that this was not the case, and that the form and size of the loading area affect the p(z) function, Letoshnev originally preferred the relationship:

$$p = k_L z \tag{2}$$

where k_L was a soil "constant." Equation (2) was favored by Academician Goriachkin, who was undoubtedly familiar with works by Grandvoinet, Gerstner, and Schultz (Bekker, 1956). However, Bernstein also used equation (2) in the following form:

$$p = k_B \sqrt{z} \tag{3}$$

where coefficient of soil sinkage k_B was defined by:

$$k_B = a'U + a''A \tag{4}$$

In equation (4) value U denotes the perimeter and A, the area of the loading surface. The terms a' and a'' are coefficients of empirical nature. Equation (3) apparently prompted Letoshnev to expand Bernstein's concept, and to generalize equations (2), (3) and (4) as follows:

$$p = k_B z^n \tag{5}$$

where n was soil exponent, in sinkage.

Bernstein's equation of 1913, adopted by Letoshnev in 1936, resembles the equation developed in Germany by Kögler (1933) and in the United States by Housel (1940), where the shear-perimeter area played an important role.

It should be noted, however, that Bernstein originally also considered other equations such as:

$$p = k' (1-e^{-nz}) \tag{6}$$

which was an example of a simple fitting of the experimental p(z) curve with an approximate function. Since Bernstein tested the effect of the plate size on soil "constant" k_B, he was not too happy with the result, and tried:

$$p = k' \sqrt{A} (1-e^{-nz}) \tag{7}$$

and

$$p = (k'' \sqrt{A} + k''' A) (1-e^{-nz}) \tag{8}$$

Letoshnev did not report these conjectures but concentrated solely on equations (3), (4), and (5), following closely Bernstein's reasoning.

Assume a rigid wheel pulled distance s. Then, the work spent equals Rs, where R is the motion resistance. Work E_o spent on soil deformation in length s and width b is $E_o = pbs$, and

$$Rs = pbs$$

hence,

$$R = pd = bk_B \int_0^z z^n dz = \frac{k_B b z^{n+1}}{n+1} \tag{9}$$

As it will be shown later, the fundamental form of equation (9) has provided one of the simplest and most reliable solutions for a rigid wheel, practically unsurpassed to this day (Schuring, 1968; Bekker, 1969). However, in order to consider the effect of the size of the wheel, both Bernstein and Letoshnev accepted the following: since k_B depends on the form and size of the wheel, the elementary work of motion resistance R on distance δs may be defined as

$$R\delta s = \delta s \int_0^z k'_B z^n dz = (\delta s k'_B) \int_0^z z^n dz$$

But $k'_B \delta s = k_B$, where δs is such a length of the contact area, which at wheel width b defines elementary area of 1 cm^2. According to Bernstein:

$$k_B = a'U + a''A = k'_B \delta s$$

In this equation, perimeter U relates to the area of width b, along which ground deformation occurs. It is equal to two side secants of the wheel, i.e., $U = 2\delta s$. And the elementary area of deformation is $A = b\delta s$. Hence,

$$k'_B = 2a' + a''b \tag{10}$$

and,

$$R = \int_0^z (2a' + a''b)\, z^n dz$$

and,

$$R = \frac{(2a' + a''b)\, z^{n+1}}{n+1} \tag{11}$$

Values a' and a", and hence k'_B, were assumed as soil parameters quasi-independent of the size of the loading area. Letoshnev used soil values, equation (10), as a basis for calculating performance, and loads for certain wheel dimensions of four-wheeled

carriages (Bekker, 1956). He expanded the study over many variations of those vehicles in a number of fundamental soil types and their values, and tested extensively four-wheel carriages with various axle loads and wheel diameters. Subsequently he compared the results with "soil values" by Morin, Gerstner and Bernstein. The conclusion was that Bernstein's definition of p(z) gave the best results.

A simplification of Bernstein's soil values a' and a" was introduced by himself on the basis of tests by Morin (1840). It was confirmed by Letoshnev on the basis of tests performed by the Russian Highway Research Bureau (TsUMT) and led to the modification of equation (10) in the following form:

$$k'_B = 2a' \left(1 + \frac{a''b}{2a'}\right)$$

Since experiments performed on hard sandy ground, with wheels of varying b, and on a sand layer 12 to 15 cm thick, showed that $a''/2a' \cong 0.27$,

$$k'_B = 2a' (1 + 0.27b) \tag{12}$$

Figures for a', for rigid wheels, quoted by Letoshnev are:

Table 1

Soil	a'
Mowed grass moist	71.1
Mowed grass soft	11.2
Potato field	7.5
Potato field - frozen	17.8
Ploughed thawed field	5.7
Stubble, moist	9.8
Stubble, dry	20.9
Stubble, soft	8.9

The experiments performed with horse driven wagons were mainly concerned with second-pass vehicle performance, which in a sense has obscured the meaning of k_B, k'_B, a', and a" as deduced from the first pass, single wheel performance. Perhaps this was the reason why Letoshnev confined his work to the rigid wagon wheel configurations in firm soil, instead of to a generalized solution for any loading area, in any kind of soil. At least this was the conclusion of this writer, since he was first exposed to Bernstein-Letoshnev theory in 1950.

In general, sandy soils, according to Letoshnev's experiment, showed the following k'_B values:

Loose dry sand	$k'_B = 1.1\,b$
Sand and humus	$k'_B = 2.2\,b$
Sandy track	$k'_B = 2.8\,b$

Clayey soils also were investigated by means of four-wheel wagons. Since the clay compacts under consecutive passes, k'_B increases as shown below:

Table 2

Wheel Width	Soil Coefficient k'_B			
	1st Pass	10th Pass	20th Pass	30th Pass
13/4" (4.45cm)	17.3	18.9	21.6	21.6
21/2" (6.35cm)	23.4	21.4	27.0	25.0
31/2" (8.89cm)	26.4	30.4	29.0	29.0

The values of k'_B were calculated from dynamometric carriage tests with the help of equation

$$R = \frac{2W^{3/2}}{3(z+1)^{3/2}\sqrt{bk'_B}}\left(\frac{2z}{\pi\sqrt{D_1}} + \sqrt{\frac{1}{D_2} + \frac{4z^2}{\pi^2 D_1}}\right)^{3/2} \tag{13}$$

where z is the ratio between the front axle load W_1 and the rear axle load W_2; $z = W_1/W_2$; wagon weight $W = W_1 + W_2$; and D_1 and D_2 are front and rear wheel diameters, respectively. Exponent of soil sinkage n was assumed to be 1/2, in accordance with Bernstein's measurement. On the basis of these calculations Letoshnev deduced that k'_B in clayey soils changes with wheel width b in the following fashion:

$$k'_B = a' + a''b \tag{14}$$

where b is in cm. Thus in the assumed soils, coefficients a are as shown below:

Table 3

No. of Passes	a'	a''
1	9.0	2.16
10	7.4	2.59
20	9.0	2.1
30	12.0	1.7
Average	10.0	2.1

The average for clayey soils was assumed in the following form:

$$k'_B = 10 + 2.1\,b$$

Loamy soils also were subject to measurements by means of four-wheel wagons. Experiments were performed for wheels of various diameters and b = constant. Results showed no marked differences for sandy soils, with average value of k'_B=5.0 for b = 4.45 cm. Thus for loam,

$$k'_B = 21.6 \qquad \text{for } b = 4.45 \text{ cm.}$$

Gravel tests showed:

Table 4

b =	1-3/4"	2-1/2"	3-1/2"
k'_B =	80.5	66.8	48.2

Forest roads full of organic matter and debris gave:

$$k'_B = 5.5 + 1.1\,b$$

Country roads were defined in the table below:

Table 5

Road	k'_B
Loose Sandy	2.2 b to 2.6 b
Hard Sandy	4.0 b to 6.0 b
Clayey	7 + 1.2 b to 10 + 1.3 b
Forest	5.5 + 1.1 b
Gravel	11.3 + 7.3 b

To repeat, k'_B here is the ground-bearing capacity in kilograms at 1 cm sinkage of the wheel.

The brief review of work by Letoshnev leads to the following summary:

- His experiments and theoretical generalizations based on Bernstein's concept of soil values for the fixed value of n = 1/2 were concerned with four-wheel horse-driven wagons.

- The soil values $k'_B = 2a' + 2''b$ were determined from wagon tests on the basis of rather complex equation subject to assumption of the effect of repetitive passes.
- The whole work led to the classification of payloads of horse-driven carriages on various country roads, and on agricultural fields.
- His study was not related to self-propelled vehicles in contrast to work by Bernstein (steam ploughs).
- In consequence, Letoshnev's work was lost for a whole generation of automotive engineers.

The last conclusion can be seen in the fact that the Automotive Tractor Handbook published by Kristi (1938) two years after the publication of Letoshnev's work (1936) does not even mention any soil values, or Bernstein or Letoshnev. Instead, it dwells on motion resistance of wheels which was expressed in terms of empirical coefficients. Similarly a collective work on tank theory (Kristi, 1937) ignores soil-vehicle interface. And much later Professor Lvov (1952) did not produce any soil values or the theory of a wheel, when considering isobars of pressure distribution under a circular footing or bearing capacity of agricultural soil, somehow expressed in kg/cm^2, at various moisture contents. The nearest to the generalization of the soil values was his diagram showing relationship between pressure and sinkage based on a far too simple expression of load-sinkage relationship: $p = kz$. This rather surprising course of events indicates that the Russian research in soil-vehicle relationship carried out between the early thirties and fifties was not systematically organized and coordinated.

An explanation of this phenomenon appears simple. In the automotive field, technological problems of maintainability, reliability, and production cost have been always more time and money consuming than soil-vehicle research. Thus the management of various R&D establishments was more hardware-oriented than theoretically minded. And the objective of numerous government Research Institutes and Chairs of Automotive and Tractor Engineering that existed at major universities was directed toward (Zimelev, 1957):

- selection of optimum engine power for the given vehicle type and class
- selection of the type and parameters of the transmission
- reduction of motion resistance
- increase of vehicle "mobility," through solution of problems such as selection of optimum number of axles, load distribution, etc.

- reduction of fuel consumption
- rationalization of special vehicle and tractor loads (one or more trailers)
- storage of surplus energy of the engine, and its subsequent utilization when accelerating, or driving on difficult roads (?)
- improvement of steering
- weight reduction and diminishing dynamic loads of the transmission and the running gear
- solution of practical problems of reliability, utility, and performance.

Obviously in such a program nobody thought that Letoshnev's horse-driven carriages and their soil-vehicle relationship would have any relation to motor vehicles.

Post Letoshnev Era

The difficult access to Russian literature makes it somewhat uncertain as to what was the real trend in terrain-vehicle studies immediately after the post Letoshnev era, and what was just this or another idea of soil values proposed by enthusiastic researchers.

To distinguish between the two, a review of school of thought at major research organizations was analyzed, and its "durability" as well as the extent of acceptance inferred. With the chronology of events closely recorded, a basis for sound conclusions was thus hopefully established.

Nonetheless, it was an arbitrary act for a historian to define the end of one era and the beginning of another. With this reservation the Letoshnev era was designated as the period when a penetration plate (or wheel) that produced k_L, k_B (or k'_B), and the n-soil values, was used without any concern for horizontal shear forces τ producing soil thrust.

If this writer is correct, that era ended about 1958 with an article about a rotational penetrometer, published in a bulletin of the All Russian Research Institute of Mechanization and Electrification of Agriculture (VIMESH). The method was designed for "determining physical-mechanical soil properties needed for the evaluation of soil as an engineering material, and as a locomotion medium for tractors and agricultural machinery" (Tsymbal, 1958).

The apparatus which will be described in Chapter IV claimed to measure the coefficients of:

- soil penetration k'_B
- soil shear τ
- soil-metal friction μ_0.

The device was made of a smooth cone which rotated when forced into the ground. But the measuring of k'_B was performed by a small rigid "standard" wheel attached to the gadget. Knowing wheel dimensions D and b, wheel load W, and motion resistance force R, the value of k'_B could be determined from the Bernsteinian equation (for n = 1/2):

$$k'_B \cong \frac{3}{4R^2 b} \left[\frac{W}{\sqrt{D}}\right]^3$$

(see Bekker, 1956). This, of course, was not quite new, except for cone rotation which allegedly gave the coefficients of friction of metal-to-soil and soil-to-soil, including "adhesion" and "cohesion" which was not mentioned as a separate value.

The lack of any data correlating these coefficients with vehicle performance does not enable one to deduce what kind of success Tsymbal had. Since his idea was not mentioned again, it is almost certain that Tsymbal was not successful, particularly with his "standard" wheel method which entailed scale effect apparently never seriously explored by the Russian investigators.

However, a similar concept was revived later in the form of a "three cone" instrument for soil measurement (Matsepuro and Runtso, 1951) and in a "cone-cum-blades" device (Rokas, 1960), curiously enough without any reference to the work by Tsymbal, as will be discussed later.

In any case, Tsymbal's work was instrumental in focusing future efforts on soil shear, thus inaugurating a new era in a search for a more complete set of soil values. The search, however, was tortuous and slow.

In the recent book published by the editors of the Mechanical Engineering periodical devoted to machine design,* one of the leading contemporary students of the optimization

* Machinostroyenie

of tractor parameters, Guskov (1966) described the history of early Russian work and first referred to the classical work on soil mechanics by Sokolovski (1942). This, however, appears to have been more a tribute to the distinguished member of the Russian Academy of Sciences than an attempt to use his methods in locomotion. Next, he did not introduce soils beyond the descriptive standards of civil engineering mechanics, such as particle size distribution and plasticity index. In addition, his introduction was concerned with vehicle performance parameters such as the coefficient of "adhesion" and motion resistance, and their relation to moisture content, without referring to soil properties of mechanical nature. In this historical outline he only quoted an early American paper by Gross and Elliott (1946) and the Russian work by Babkov (1959) and Aziamova (1959). This led him to the conclusion that "because of lack of data, the problem (of soil values) requires further study," Such a statement characterized in an authoritative manner the immediate post-Letoshnev state of the art, and was rather surprising since it indicated that, basically, no new work on soil values and their relation to moisture content was conducted until more recent time.

A spot check seems to confirm this conclusion. Vernikov (1940), for example, was only concerned with the question that soil parameters k_B and n do not include time element; i.e., they cannot be used for prediction of wheel sinkage at varying speeds of locomotion. Proposing p = kz equation with soil values n = 1, he introduced inertial forces of soil deformation. This led him to expressing soil value k_v in terms of densities γ and γ' measured before and after compaction, respectively:

$$k_v = \frac{\gamma\gamma'}{2(\gamma'-\gamma)}$$

however the reported experimental verification of this method raises serious doubts as to its correctness. Since k-value interpreted in terms of densitites ratio was not found by the present writer in other publications, the above equation apparently has only an historical value.

Saakyan (1953) departed from sinkage soil values, and considered wheel slip. In this exercise he described soil characterized by moisture content, density, porosity, and water capacity. He proposed that wheel slip i_o may be expressed as a function of sinkage z in the following form:

$$i_o = k'_v z^{n_v}$$

where, in average, coefficient $k'_v \cong 0.012$ and $n_v = 1.1$ depending on wheel size and load. Obviously the new soil "values" k'_v and n_v had totally different meaning and significance from the Bernstein-Letoshnev concept, as they referred to slip-sinkage function of unknown origin and reliability.

But Gutyar (1955) used Bernstein's soil values k_B and $n = 1$ ($p = kz$), referring to k_B as a "volumetric coefficient of soil deformation" (kg/cm^3). He criticized, however, the adequacy of the $p = kz$ relationship and ventured into empirical study of elasto-plastic soil deformations. To this end he proposed two empirical moduli of soil deformation, k_G and k'_G, which purport to characterize the elastic and plastic deformation of soil, respectively, in lieu of one coefficient k_B. Both coefficients, it was suggested, could be determined by measuring the sinkage of the wheel and the rut depth which shows elastic soil rebound (see Chapter V).

Kolobov (1960), who reported tests on pressure distribution under tires, characterized soils only by density measured at depths of 5, 10, and 15 cm, and by the moisture content. This was totally inadequate because pressure distribution depends on other soil parameters (Bekker, 1956).

The diversity and lack of coordinated efforts characterizing these approaches are obvious. This was stressed later by Kuznetzov (1962), who was primarily concerned with tillage and ploughing. He emphasized that penetration test results depend on the size and form of the penetrometer, and directed his attention to a shear test by means of an instrument equipped with two angular blades, which will be described in Chapters III and IV.

Conclusions reported by Guskov to the effect that soil deformation depends on time also appears to be either premature or anachronistic. He referred to work by Ishlinski (1938) who proposed the solution based on the following interdependence between load p deformation z, modulus of rigidity G, viscosity μ, and time t:

$$p = Gz + \mu \frac{dz}{dt} \tag{15}$$

This equation may be recognized as Thomson's model of elasto-plastic behavior. It was discussed by various soil researchers before and after 1950 (see Bekker, 1956),

and thus far did not resolve original problems of land locomotion, since the model does not fit the soil. The history is the same as that of Maxwell's model, which was proposed for snow (Bucher, 1948). It thus appears certain that no original or important work on the problem was conducted since Letoshnev; Guskov and another authority on land locomotion, Katsygin, were fully aware of Thomson and Maxwell's model and seem to have worked on it, since the results of soil tests using these models were published by "Trudy instituta fiziki zemli" (Works of Soil Physics Institute) in 1953.

Katsygin (1964), describing the "state of the art" and the preceding developments, even went back as far as Mohr's theory of soil shear and to the fundamentals of soil shear based on Terzaghi. But this he did very much in the style of Bekker's "Theory of Locomotion," which elaborated at length on the same problems and was translated and published in Russia in 1957 (see Traktory i Selskohozyainye mashiny, No. 1, 1968). Katsygin as well as Guskov also reported Bernstein-Letoshnev's approximation of load-sinkage relationship $p = kz$ and $p = k_B z^n$. They both were fully aware that k's were a function of the form of the loading area, and were not satisfied with the fractional dimension number of n. In this context Katsygin quoted Saakyan (1959) who proposed using dimensionless value $\lambda = z/D$ instead of z, where D was the diameter of the loading area. Thus for a circular plate having area $A = \pi D^2/4$:

$$\lambda = z/\sqrt{4A/\pi}$$

and

$$p = k_s \lambda^n \tag{16}$$

where k_s is a coefficient of ground deformation (kg/cm^2). Physically, k_s defines the ground pressure corresponding to sinkage z equal to the diameter of the loading place. n was again the Bernstein-Letoshneve exponent of sinkage. Dimensionless relationship based on z/D ratio was also proposed later by Reece (1965).

Values of k_s and n for non-chernozem soils were shown in Table 6 after Katsygin (1964).

Table 6 reflects the size of the plates used in tests, which were not specified. New developments that followed coped with special "soil" conditions.

Table 6

Basic Soil	Surface Type	Moisture Content (%)	k_s kg/cm^2	n
SAND	Unploughed Stubble Settled ploughed	14-16 11-13 12-14	10-12 7-8 4-6	0.50-0.60 0.40-0.45 0.35-0.40
LOAM (loose)	Unploughed Stubble Settled ploughed	13-14 12-13 12-13	18-20 12-18 8-10	0.60-0.70 0.45-0.50 0.45-0.50
LOAM (medium)	Unploughed Stubble Settled ploughed	10-11 12-14 16-17	16-24 13-19 6-10	0.60-0.80 0.50-0.60 0.35-0.40
LOAM (heavy)	Unploughed Stubble Settled ploughed	19-20 13-16 12-14	16-22 13-20 8-11	0.60-0.75 0.55-0.70 0.45-0.50
CLAY (loose & heavy)	Unploughed Settled ploughed	12-15 10-13	20-25 10-16	0.60-0.90 0.50-0.60

For very wet soil, particularly of turf or moss type, equation (16) did not fit the experiment. Hence Korchunov (1948) proposed another equation without mentioning its similarity to the original Bernstein equation (6):

$$p = p_{KO}\,(1-e^{-z/k_{KO}}) \tag{17}$$

Here z is sinkage of the loading plate (cm), and k_{KO} is soil parameter (cm). Again, value of p_{KO} depends on the form of the loading area. To avoid such inconvenience, Katsygin referred to Housel (1929) rather than to Bernstein (1913) and Letoshnev (1936), proposing:

$$p_{KO} = A_o + B_o\,\frac{U}{A} \tag{18}$$

where A_o is the bearing stress of the soil (kg/cm^2); B_o relates to the shear stress along the perimeter of the loading area. U and A are the perimeter (cm) and the area (cm^2) of the penetrometer plate, respectively.

Azyamova (1959) showed that for turf, p_{KO} and k_{KO} depend on moisture content. As a result the Central Scientific - Research Institute for Mechanization and Electrification of Farming in Chernozem Zone of U. S. S. R. worked out a relationship between k_{KO} and moisture content MC in the following form:

$$k_{KO} = k_{KL} \left[1 - \gamma_1 \frac{MC - MC_L}{10} - \gamma_2 \frac{(MC - MC_L)^2}{100} \right] \tag{19}$$

where k_{KL} is a coefficient (measured in cm) of organic soil, at moisture content corresponding to the lower limit of plasticity interval; MC_L is moisture content of the ground at the lower limit of plasticity index; MC is current moisture content; and γ_1 and γ_2 are empirical, dimensionless coefficients.

The change of the range of bearing capacity p_{KO} with moisture content is, according to the Institute (Katsygin, 1964):

$$p_{KO} = \frac{p'_{KO}}{N_{PL}} (MC_H - MC) \tag{20}$$

where p'_{KO} is bearing capacity at the lower limit of plasticity index (kg/cm^2); N_{PL} is plasticity number ($N_{PL} = MC_H - MC_L$); and MC_H is moisture content at the higher limit of plasticity index. Values of the discussed coefficient are shown below, after Katsygin:

Table 7

Turf Soil	MC_H (%)	MC_L (%)	N	γ_1	γ_2	k_{KL} (cm)	p'_{KO} kg/cm^2
Wet	88	78	10	0.11	0.10	8.8	1.30
Dry	86-87	72-76	11-14	0.12	0.10	8.4-8.6	2.17-2.35
Ploughed Settled	84	60	24	0.13	0.11	8.0	3.58

In all these attempts the trend toward establishing better soil values is obvious. It was based on curve fitting into experimental p(z) equations as originated by Bernstein; in this work many possible ways and means were explored in order to provide mathematical models of load-sinkage relationship. Since much of this work antidates similar work published in the United States or elsewhere, the original pioneering spirit in establishing a theory of off-road locomotion based on a semi-empirical soil-value system cannot be denied to the Russian researchers.

More evidence to that effect is seen in works by Professor Pokrovskii, briefly reported by Katsygin (1964), though application of Pokrovski's theory of "contact-induced-strength" of granular masses has not been seen by this author. In general, the abundance of semi-empirical, engineering-type solutions seems to indicate that practical approach has been favored since the time of Letoshnev, rather than more rigorous but no more accurate theories.

In this vein Troitskaya (1947) developed another empirical approach to soil deformation (originally proposed by Pokrovskii) in which load pressure p was expressed as a function of sinkage z in relation to the height h of deformed soil prism: $\lambda = \frac{z}{h}$; she assumed then that for compression:

$$p = p_c \left(e^{k_T \lambda} - 1\right) \tag{21}$$

and for shear:

$$\tau = \tau_o \left(1 - e^{-k_T \lambda}\right) \tag{22}$$

For a simultaneous shear-compression load:

$$\sigma = \tau_o \frac{p_c \left(e^{k_T \lambda} - 1\right)}{\tau_o + p_c e^{k_T \lambda}} \tag{23}$$

where τ_o is ultimate shearing strength and p_c is maximum bearing strength; k_T is dimensionless coefficient. Equation (22) is equivalent to equation (17).

The so-far discussed linear and exponential functions expressing load-deformation of soil in terms of various k and n symbols were often criticized on ground of not fitting well the experimental curves, or more often, on a theoretical ground of the lack of physico-mathematical consistency (Katsygin, 1964; Guskov, 1966), all of which does not necessarily affect the practicability of such functions.*

This puritan criticism was taken as a justification for expressing p(z) function in terms of soil values based on hyperbolic tangent functions, instead of the exponential ones (Katsygin, 1962; Matsepuro and Katsygin, 1963). Katsygin (1964) and Guskov (1966)

* "Mathematical" objections were raised against fractional n-values and their seemingly lack of physical meaning.

dwelled at length on these functions which seem to indicate an attempt at establishing a trend, at least at the Minsk School of thought, a trend which survived the decade of the nineteen sixties and is still strong. It will be seen, however, that while this trend is undoubtedly authoritative and spreading, at least in the field of agricultural tractor engineering, occasional revision by others and their continuing use of exponential functions indicate that the issue has not been totally closed, at least in automotive engineering.

It may seem obvious that the hyperbloic tangent function must fit well an experimental load deformation curve of natural soil, if one looks at the shape of such a function. But nobody thought about it. Katsygin was the first to discover the similarity and proposed that load p be expressed as a function of sinkage z in the form:

$$p = p_{KA} \tanh \left[\frac{k_{KA}}{p_{KA}} \right] z \qquad (24)$$

where p_{KA} is the bearing capacity assymptotically reached by the load deformation curve (kg/cm^2); k_{KA} is coefficient of soil deformation (kg/cm^3). The proposal was based on a lengthy mathematical argument, which appears to be circular.

It is interesting to note that claims to the effect of equation (24) being superior to exponential and other equations were not necessarily made on the grounds of better accuracy of curve fitting, closer prediction of performance, etc. Apparently, this was not the main issue. Instead, mathematical generality of the hyperbolic tangent function was praised because, if the function is developed in series, the first term is $p = k_B z$, i. e., it represents Bernstein's formula for $n = 1$. It also was shown that equation (24) may be made equivalent to $p = p_o (1-e^{-z/k_{KA}})$, i. e., to Korchunov's and Troitskaia's equations.

Katsygin (1964) checked the measured and predicted soil values using the tanh-function, and was satisfied with the result, although he was aware that the values depend on the plate size. Table 8 gives p_{KA} and k_{KA} based on his experiments.

Determination of coefficients p_{KA} and k_{KA} was made on the basis of two tests for pressures p_1 and p_2, then:

$$p_{KA} = \frac{p_1}{z_1\sqrt{(2p_1/p_2)-1}} \qquad k_{KA} = \frac{p_1 \tanh^{-1}\sqrt{(2p_1/p_2)-1}}{z_1\sqrt{(2p_1/p_2)-1}} \qquad (25)$$

Table 8

Basic Soil	Surface Type	Moisture Content	p_{KA} kg/cm^2	k_{KA} kg/cm^3
Sand	Unploughed	14-16	12.9 - 14.3	8.3 - 11.0
	Stubble	11-13	8.1 - 9.0	6.8 - 8.2
	Settled Ploughed	12-14	4.5 - 6.6	4.1 - 6.5
Loam, Loose	Unploughed	13-14	24.2 - 25.8	13.6 - 16.6
	Stubble	12-13	14.3 - 20.9	10.9 - 17.4
	Settled Ploughed	12-13	9.6 - 11.6	7.3 - 9.7
Loam, Medium	Unploughed	10-11	27.4 - 31.0	11.1 - 19.9
	Stubble	12-14	16.8 - 22.7	10.7 - 17.4
	Settled Ploughed	16-17	6.8 - 10.9	6.1 - 10.8
Loam, Heavy	Unploughed	19-20	24.9 - 28.5	11.6 - 18.2
	Stubble	13-16	18.9 - 24.7	9.8 - 17.4
	Settled Ploughed	12-14	9.5 - 12.8	7.3 - 10.4
Clay	Unploughed	12-15	32.3 - 46.2	12.7 - 20.7
	Settled Ploughed	10-13	12.5 - 19.1	8.3 - 14.7

For the sake of time economy the experiments were performed in such a manner that sinkage $z_2 = 2z_1$. This is why only the value of z_1 (and number 2) is noticeable in equation (25).

The effect of plate size upon p_{KA} and k_{KA} clearly emerged from the tests. Although the plates used did not differ much in size, they produced unmistakable results:

plate 11 cm dia.: $p_{KA} = 6.03$ kg/cm^2; $k_{KA} = 2.3$ kg/cm^3

plate 14 cm dia.: $p_{KA} = 7.0$ kg/cm^2; $k_{KA} = 1.2$ kg/cm^3

It was obvious that the soil values defined under these conditions cannot be used indiscriminately for prediction of behavior of different sized plates.

W. W. Rozhdestvenskii, as reported by Guskov (1966), investigated turf-type soil with plate diameters corresponding in area size to the size of the load-carrying areas of tracks of tractors. The results display a strong effect of plate size on p_{KA}. Much greater effect of plate size upon k_{KA} also was discovered. Extensive testing was reported to lead to the following empirical formula for turf:

$$k'_{KA} = \frac{k_s}{\sqrt{F}} \tag{26}$$

where k_s is the soil value (kg/cm^4) obtained by means of the test plate from Saakyan's equation (38). F is the ground contact area under investigation in cm^2. For the sake of safety, however, measurement of k_{KA} and p_{KA} were recommended to be taken with plate sizes equal to the sizes of load-carrying areas of the investigated vehicles (Guskov, 1966). Such procedure, of course, is ultimately equivalent to using the vehicle itself as a soil testing instrument.

Obviously this was found rather inconvenient and of limited use; thus such authorities as Matsepuro and Selitskii (1961) proceeded then with the Bernstein-Letoshnev equation $p = k_B z^n$ involving dimensionless sinkage z related to plate diameter $D(\lambda = z/D)$ in the form of:

$$p = k''_{KA} \lambda^n \tag{27}$$

This equation was similar but not equivalent to the equation later proposed by Reece (1965) in England. Equation (27) was generalized for tracks using track width b instead of plate diameter D. This move resembled the procedure adopted earlier by Bekker (1956, 1960), and led to the formula:

$$p = k'''_{KA} \left[\frac{z}{b}\right]^n \tag{28}$$

While load penetration equations were distinctly Russian, with a general acknowledgment of their Bernsteinian origin, the shear-slip curves were clearly recognized as solutions proposed by Bekker (1956). Specific references to that point were made, among others, by Katsygin (1964) and Guskov (1966). However, G. I. Pokrovskii also was quoted as an independent co-author of the Bekker-type shear-slip equation, and his formula was produced by the previously mentioned authors in the form:

$$\tau = (c_1 e^{-c_2 s} + c_3)\ (1 - e^{-c_4 s}) \tag{29}$$

where c_1, c_2, c_3 and c_4 are empirical soil constants; s is shear deformation (cm).

Considering equation (29) inadequate, Katsygin (1963) proposed a hyperbolic function for shear-deformation in the following form:

$$\tau = \mu_m p \left[1 + \frac{\mu_{KA}}{\cosh \frac{s}{k_\tau}}\right] \tanh\left(\frac{s}{k_\tau}\right) \tag{30}$$

k_τ is the coefficient of deformation (cm); s is shear deformation (cm); and μ_m is the so-called coefficient of friction in motion. Compound coefficient μ_{KA} is expressed by equation:

$$\mu_{KA} = \frac{4\mu'_o - 3\mu_m}{2\mu_m} \qquad (31)$$

Here, μ'_o is the so-called coefficient of friction at rest. Value of k_τ is expressed by:

$$k_\tau = \frac{s}{\cosh^{-1}\left[\frac{1 + \sqrt{1 + 8a^2}}{2a}\right]} \qquad (32)$$

where $a = [(2\mu'_o/\mu_m) - 1.5]$, if μ'_o/μ_m is enclosed between 1.5 and 3.0.

Theoretical background of these equations published by Katsygin (1964) shows extreme complexity in the line of thought; one may question the purpose of this attempt. To fit an experimental shear-deformation curve with an equation so complex and so different from the simple and adequate Coulombian solution with an attenuating function (Bekker, 1956) appears questionable.

Experimental evidence clearly shows that peaked shear-deformation curves which Katsygin had in mind, and which led to his complex equation, have little practical application in ground locomotion, and that a much simpler American equation (Janosi, 1961) serves the purpose very well, indeed.

Solution (30) becomes unmanageable if it is recognized that the relationship between coefficients of friction μ'_o and μ_m is strongly affected by load p. This relationship varies from soil to soil, and equation (30), if generalized, must include separate experimental curves as shown by Katsygin. Guskov (1966) apparently did not like that, and dwelt on the problem, referring to a much earlier work of a similar nature by Antonov (1949).

This tendency to show the originality and to explain the present in terms of the past Russian efforts is seen in the most meticulous and sometimes reverent referencing to old time researchers, coupled with a general tendency to the omission of contemporary foreign references.

Coefficients of friction μ'_o and μ_m obviously include both friction and cohesion of soil. Thus, although the simple Coulomb's equation was known to everyone concerned (see Katsygin, 1964) the values of the apparent coefficient of soil friction ($\tan\varphi$) and cohesion (c) were not explicitly introduced and measured. This may have happened because of Guskov's (1966) concern with the "scale effect," although in conversation with Bekker he agreed that the errors involved could be managed, for practical purposes. In any case Katsygin's soil shear-values were dependent on the vehicle size used; any instrumentation for measuring soil values μ'_o and μ_m involved an error, which had to be carefully considered, in the extrapolation of results obtained.

As a sample of shear values μ'_o and μ_m, Guskov (1966) quoted the following figures (Table 9):

Table 9

Tractor Weight kg	Ground Pressure p kg/cm^2	Loam Soil μ'_o	Stubble μ_m	Turf Soil μ'_o	Stubble μ_m
1,000	0.076	2.6	1.96	1.34	0.84
3,000	0.23	2.0	1.4	0.94	0.57
5,000	0.38	1.64	1.2	0.77	0.48
8,000	0.6	1.4	1.2	0.65	0.4
11,000	0.83	1.16	0.98	0.55	0.37
15,000	1.14	0.9	0.83	0.53	0.36
Ground Contact Area = 13,200 cm^2					

Generally speaking, Katsygin-Guskov's shear values are not different in basic concept from Coulomb-Bekker's soil parameters. This was already recognized when Sofian (1960) published an article about tractor pull in an agricultural magazine. In this article he cited Bekker's (1955) paper and reproduced from it a number of pull-slip curves, plus his experimental graphs. He measured tangential forces in tractor cleats, and found that the experimental data confirm Bekker's theory, which was based on soil friction φ, cohesion c, and soil slip coefficients K_1 and K_2. Thus Sofian in a sense affirmed the validity of the Coulomb-Bekker (1955) equation and K_1, K_2, c, φ soil values along with Katsygin's values. However, since he tried to introduce cleat dynamics due to load change under the bogies, his interest centered around the empirical refinement of the dynamic solution, rather than on the soil values themselves.

The post-Letoshnev era thus ended with new solutions, though no more practical than those proposed by Coulomb, Bernstein, Letoshnev, Bekker, and Reece. The apparent lack of soil values, independent, at least for practical purposes, from the size of the loading areas and the load, was responsible for what may be considered an inconsistency in Russian evaluation of soil-vehicle relationship, since they realize the seriousness of the problem.

The inconsistency is seen in various authors using various p(z) and τ(p) functions based on different soil values that depend on specific circumstances of size-load combination.

As a result, comparative evaluation of competing terrain-vehicle systems and performances was far away – though subsystems analysis in optimization of certain vehicle performance and parameters were very close (see Guskov, 1966).*

Agricultural vs Automotive Soil Values

The general trend in mathematical modelling of experimental load-sinkage and slip-shear functions, i.e., the definition of soil values, was described in the previous section. As shown, the trend started in German agriculture in 1913 by Bernstein, and continued in Russian agriculture, mainly under the influence of work by Letoshnev. Russian automotive engineers, though concerned with off-road locomotion, did not participate much in this development. The situation was different in the United States. U.S. agricultural engineers have seldom considered seriously the theory of soil-vehicle interface, and it was up to American automotive engineers at Detroit Arsenal to establish a first systematic study, and a formal off-road locomotion laboratory which pioneered much of what is now an internationally recognized discipline (Proc. 1st, 2nd, and 3rd Int. Conf. on Terrain-Vehicle Systems, 1961, 1966, 1969).

In this section, attention will be concentrated on the interaction between Russian agricultural and automotive engineers, and on their attempts to foster a more theoretical approach to soil measurements, as compared to a similar activity in the United States.

* The subsystem is defined as a specific vehicle component or aspect performance in the given soil. Guskov among others, optimized wheel and track subsystems from the viewpoint of traction and design.

The review will be primarily based on information published by two leading magazines: "Traktory i Sielskokhczyanye mashiny" (Tractors and Agricultural Machinery) and "Avtomobilnaya Promyshlennost" (Automotive Industry), including other publications, whenever available. The development of soil values will be described as much as possible in a chronological order, in order to preserve the continuity of thought evolved.

Little information is available for the period covering World War II, and not much was accomplished before the war, except for the material attributed to Bernstein-Lekoshnev. One of the first remarkable post-war contributions, as far as it could be ascertained, was the article by Omelianov (1948), published in the journal of agricultural engineering. Omelianov attempted to utilize indirectly Letoshnev's experience with the rigid wheel, for evaluation of pneumatic tires. To this end he started with a primitive dimensional analysis, which included tire "constraints" but no soil "parameters." The latter were added later, in a kind of postscript. From this approach, Omelianov deduced an equation of motion for tire resistance, which resembled in structure the Bernstein-Letoshnev equation, inasmuch as it included soil value k, which was based on the unspoken assumption of n = 1. k was expressed in kg/cm^3; since it depended on tire type, as well as on soil properties, Omelianov introduced two correction factors, C_1 and C_2 (see Bekker, 1969). The equation took the form of:

$$R = C_1 W (p_i/k_{OM} D)^{1/3} + C_2 (W^4/p_i D^2)^{1/3}$$

The second term defined the portion of rolling resistance which depends on tire carcass stiffness, and is of no interest at this time. The first term defined the resistance R' due to the rut making and defined soil-tire interface. By regrouping:

$$R' = \frac{C_1 W_{P_i}^{1/3}}{(k_{OM} D)^{1/3}} = \left(\frac{C_1^3}{k_{OM}}\right)^{1/3} \left[\left(\frac{p_i}{D}\right)^{1/3}\right] W \qquad (33)$$

Equation (33) has the same dimension as Bernstein's equation for n = 1. Its first member corresponds to Bernstein's k_B or Letoshnev's k_L. In this case then $k_{OM} = C_1^3/k_B$. C_1 varies for low pressure tires between 0.35 and 0.50, in soils having $k_L = 2$ kg/cm^3, and is dimensionless. In sum, Bernstein-Letoshnev's soil values were accepted, though not named as such, and their variation with tire properties was compensated by an empirical tire coefficient, C_1, depending on soil type (see Bekker, 1969).

This was perhaps the first application of "soil values" to tire evaluation. Omelianov's work was deemed extremely important by the Editors of "Sel'khozmashiny" (Agricultural Machinery), and especially useful for the designers of agricultural tractors with pneumatic tires.

A classic textbook on Machine Design edited by Martens (serials probably published after 1943) was concerned with cross-country automobiles and non-agricultural tractors. However, although empirical coefficients of motion resistance for various soils were referred to, no soil-values were discussed. But a soil coefficient "c" was introduced, which in the equation of wheel sinkage was again equivalent to Bernstein-Letoshnev's k_L for $n = 1$. No reference to works by Bernstein-Letoshnev, Goriachkin was made. Automotive and agricultural engineers apparently were competing rather than cooperating, since even their symbols in the same equations were different. Thus the Russian automotive industries originally did not follow the lead by agricultural engineers.

This was not a unique phenomenon. A similar situation, although in a reversed sense, existed in the U. S. A. A low level activity that was left over from World War II emergency and empirics was performed by civil engineers of the Waterways Experiment Station, in Vicksburg, Mississippi. The U. S. Department of Agriculture seemed to favor its own empirical implement testing. But the Society of Automotive Engineers, recognizing the fact that very little was known about soils and vehicles, "urgently invited consideration of a long range research program for the fixed purpose of providing concrete information upon which mobility characteristic of new vehicle designs can be based... and asked that 'top notch' technical men with automotive experience be assigned to this project..." (SAE, 1945).

Although today the strict interdisciplinary boundaries between engineering professions tend to disappear, it was significant that in the 1945 to 1948 period the initiative came from the SAE and was upheld in 1954 by automotive engineers of Detroit Arsenal. Impressive results appeared in less than a decade* in the U. S. A., but they took longer in Russia.

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* See Proc. First Int. Conf. on Terrain-Vehicle Systems, Turin, Italy, 1961.

Russian automotive engineers did not consider seriously the soil-vehicle relationship, even in ten years after SAE recommendations. Zimelev (1957) in his textbook on automobile theory did not use anything beyond conventional coefficients of rolling resistance and "adhesion." He did this even with a lesser effort than Gruzdev (1944), who in his classical theory of tanks published thirteen years earlier, at least tried to analyze pressure distribution in the ground in order to arrive at a mathematical definition of rolling resistance. Zimelev's omission of any reference to soil values by Bernstein and the others is puzzling, since this distinguished student of ground locomotion quoted empirical work by McKibben of the USDA rather than the theory by Letoshnev, even though his fine exposure of automotive locomotion problems was quite theoretical.

At the same time another automotive engineer (Briuhovets, 1957) investigated tire deflection as a function of "mechanical properties" of the ground. To this end he used a box filled with a soil layer (no specification) 250 mm thick at 15% moisture. The soil was raked for each test, and compacted to such an extent that it produced "compression resistance" of the order of 0.5 to 0.6 kg/cm^2. The result: a table of soil and tire deflections for a number of wheel loads and air pressures. Tire deflections were compared with those on concrete. No attempt at explanation of results observed, or reference to Letoshnev's and Omelianov's work, were made although this would serve eminently, at this stage, as a theoretical baseline for the determination of tire-soil deformation.

The same deformations were tested in the field with a DT-24 tractor. Here again, soil was defined in terms of "compression resistance" measured in kg/cm^2. It varied from 0.5 to 3.5 kg/cm^2 (ploughed sandy field and settled sandy ground with stubble, respectively). Since sinkage obtained from these experiments varied from 15 to 10 cm, it tentatively may be deduced that the "compression resistance" was measured at that depth. The lack of mentioning any soil values apparently was due to the author's using Pigulevskii's (1929) instead of Letoshnev's and/or Omelianov's work. Samilkin (1959) also was concerned with tire deflection (rolling radius), and produced a number of figures for a number of tractors, tires, and two kinds of specified soil in a descriptive manner.

This type of work apparently became popular among some of the agricultural engineers too. Poletayev and Kolobov (1959) performed practically identical experiments with unspecified soil. It is interesting to note, however, that the following soil values were quoted in the field tests: depth (cm) and pressure (kg/cm^2) in penetration test, moisture content, and percentage of clay and sand ingredients in the ground.

Technique used by Briuhovets (1957) and Poletayev-Kolobov (1959) in registration of tire plus soil deformation, and tire deflection was, in essence, similar to that used much later by the Waterways Experiment Station (WES, 1965), which also followed the road of pure empirics.

Vasilevich (1959), another student of agriculture, was concerned with internal motion resistance of a tractor. To this end he tried to eliminate slip and soil deformation losses from dynamometric tests, and followed works by Voleidt (1952) and others. He accepted an empirical method for determination of internal motion resistance of the vehicle as proposed by academician Zheligovskii, which included dynamometric definition of losses due to soil deformation and slip. In this context, he also reviewed an equation which he attributed to academician Goriachkin (1937):

$$R = \sqrt[3]{\frac{W^4}{bkD^2}} \tag{34}$$

although it actually was the Bernstein-Letoshnev's formula for n = 1, less coefficient 0.86 (see Bekker, 1956).

Equation (34) "thus far had limited application," Vasilevich (1959) concluded, and defined resistance due to soil, in empirical, conventional coefficients. To make this more acceptable, he dwelt on Gruzdev's load distribution analysis as reported by Lvov (1952 a) and Heyde (1957) of German Socialistic Republic. This eliminated from the study any quantitative soil values, reducing the problem to a direct empirical evaluation of vehicle losses, in the field.

Curiously enough, however, soil was defined in terms such as "medium loam" with moisture content 17.62% on the surface, and 19.83% at depth of 10 to 15 cm. Note the discord between the qualitative nature of soil value definition, and the precise,

two-decimal records of the moisture content along with the crude approximation of pertinent soil depth. This indicated the shallowness of Vasilevich's contribution.

In a lengthy speculative description of tractor energy losses due to soil deformation, Vasilevich referred again to Zheligovskii and quoted him to the effect that a decrease of energy loss in motion was found to be proportional to the quadratic reduction of sinkage. Obviously such relationship could be valid only in a specific type of soil. The whole study disclosed, however, a tacit demand for precise soil value definition, though no attempt to produce it was made.

At the same time an automotive engineer named Ageikin (1959) approached the problem directly, and introduced at the onset specific definition of soil values, when considering pneumatic tires. This was based on his previous study of thin-walled tires in soft ground, and let to the following conclusions: average ground pressure p_q between the tire and the ground is,

$$p_q = C_3 p_i + p_c \tag{35}$$

where C_3 is a coefficient of tire carcass structure which varies in soft ground from 1.0 to 0.9; p_i is inflation pressure and p_c tire carcass stiffness pressure (kg/cm^2) which varies from 0.4 to 0.7 kg/cm^2; and p_q is balanced by the ground pressure acting on tire surface. The ground pressure was assumed strictly in accordance with Bernstein-Letoshnev equation:

$$p = k_L z^n$$

Contrary to Vasilevich's statement which repudiated that equation, Ageikin quoted work by Malyshev (1958) who verified soil values in this equation, not only for use with tires but also with rigid wheels. Soil values k_L and n were given as follows:

Table 10

Soil	n	k_L
Moist, cohesive	1	10-25
Cohesive in a plastic state; moist sand (majority of agricultural soils – without hard subsoil)	0.5	0.5-6
Wet, nearly saturated (turf, mud)	0	0.1-1
Wet or top soil, on stronger subsoil	1.5-3	0.001-0.1

Accuracy of prediction of tire deflection in various soils, for a number of tires, loads, and inflation pressures, using above equation with Ageikin's theory, reportedly showed good results.

Ageikin's work was undoubtedly a milestone in the post-war era as it formally reviewed Bernstein-Letoshnev's soil value system, and showed its adaptability to evaluation at low pressure pneumatic tires. Significantly, his paper was published in the "Automotive Industry" rather than in "Tractors and Farm Machinery,"

Eighteen months later another paper by Ageikin (1960) was published in the same magazine, on the same topic. "In order to evaluate vehicle mobility in a terrain, for instance, or on snow covered ground," said Ageikin, "it is necessary to know the resistance in sinkage and tractive properties of soil." Expression for sinkage resistance was accepted in the form:

$$p = k_L z^n \tag{36}$$

and the tractive properties of the ground were expressed by equation

$$\tau = c + p\mu_A \tag{37}$$

where τ is shear stress kg/cm^2; c is internal cohesion of soil; and μ_A is the coefficient of internal friction. Since μ_A equals $\tan\varphi$, equations (36) and (37) are thus the first direct quotes (though not specified as such) of the soil values introduced earlier in the United States, and known as bevameter values (Bekker, 1956, 1960).

On the basis of equations (36) and (37), Ageikin further developed his tire theory and used the following soil parameters:

Table 11

Soil	n	k_L	c	$\tan\varphi$
Clay (cohesive) moist; dry country roads	1	10-25	0.5-1.5	0.27-0.5
Cohesive, plastic soils; dry, fine grained sand	0.5 0.5	0.5-3 0.5-3	0.3-1.0 0.03-0.1	0.2-0.4 0.4-0.7
Turf, mud, without hard subsoil	0	0.1-1	0.08-0.15	0.03-0.35
Thawing soil, wet clay, fresh snow	3-1.5	0.001-0.1	0.08-0.5	0.03-0.3

Ageikin's insight into the problem went beyond the grasp of sinkage and shear parameters of soil. He also gave evidence of fully realizing the importance of slip coefficient K. This he did in a slightly different form from that introduced in the United States (Bekker, 1956, 1960; Janosi and Hanamoto, 1961).

Further evidence of Ageikin's recognition of the need for both shear and penetration data was his quotation of work by Ivanov (1950) who determined soil values closely following both Bernstein-Letoshnev and Coulomb equations:

$$c = 0.12\ kg/cm^2;\quad \tan\varphi = 0.15;\quad k_L = 0.5\ kg/cm^2;\quad n = 0.5.$$

Thus, Ivanov's quote was truly a tabulation of bevameter soil values.

It may be recalled at this juncture that the first American publication of Coulomb's equation in conjunction with off-road locomotion took place at the SAE meeting in Detroit over 20 years ago (Bekker, 1950). The paper presented at that meeting was extensively quoted and discussed in the third chapter of the agricultural "Voprosy Zemledelcheskoi Mekhaniki" (1960). In this chapter, also, other material from work by Bekker (1956) was referred to, in connection with the establishing notions of Coulombian c φ and Bernsteinian k and n values.

The authoritative series "Voprosy... " concerned with problems of agricultural soils (Voprosy Zemledelcheskoi mehaniki, Minsk 1961, 1962, 1963) continued the rational approach, although limited to Bernstein-Letoshnev's equation $p = kz$, i.e., to $n = 1$. This led to the evaluation of pressure distribution under a track catenary analogical to those by Bekker (1956) who also used that value, but only for the sake of simplicity of calculations.

In a close similarity to Bekker's work, Matsepuro and Guskov (1961) deduced the tractive effort of an agricultural tracked vehicle, assuming shearing strength of the ground τ (kg/cm) as a parameter producing soil thrust through the action of track spuds. The main component of thrust, however, was assumed to be equal to vehicle weight times the coefficient of "adhesion" μ_a; soil modulus of deformation, k, was quoted equal to 1 kg/cm^3; $\tau = 0.45$ kg/cm; and $\mu_a = 0.6$ to 1.0 for turf-type surface. It is noteworthy that the authors did not refer directly to Coulomb's equation, though in the

next chapter concerned with field testing of tracked tractors they stated that thrust H of the vehicle depends on contact area A, and load W, as shown by equation:

$$H = nW + mA$$

where n and m were called soil "parameters" instead of coefficients of internal friction, $\tan\varphi$, and cohesion c. The standardization of symbols does not seem to exist in Russia! Since the authors were familiar with Bekker's work (1956, 1957), which they quoted, and thus with c and φ concept of soil values, their semantics in dealing with established concepts of soil mechanics cannot be explained.

Thus again, when determining motion resistance of a track due to soil compaction, the authors assumed Bernstein-Letoshnev's equation, but rather unexpectedly modified it after Saakyan (1953):

$$p = k_s \left[\frac{z}{d} \right]^n \tag{38}$$

where k_s is modulus of soil deformation in sinkage, z, and d is the diameter of the sinking plate. The problem was that in this equation, k_s depends on plate size d; hence the modification did not eliminate the old deficiency.

In a numerical example calculated for an experimental tractor the following values were given: $k_s = 0.8$ kg/cm^2, $n = 0.8$; but the plate size was not specified. This leads to the plausible assumption that the test plate size equaled that of the ground contact area. Obviously equation (38) could not be applied to turf-type soils (see Bekker, 1969), and to this end the equation ascribed to Hausel (1929) and Korchunov (1948) was proposed:

$$p = p_{KO} \left(1 - e^{-z/k_{KO}}\right) \tag{39}$$

where soil values p_{KO} and k_{KO} were explained before (equation 17).

The diversity of soil value concepts thus introduced cannot be overlooked. It was further accentuated in the diversity of concepts and even denotations used by various authors for soil values. Matsepuro and Guskov, for instance, did not follow Saakyan and Korchunov without reservation. Their use of Young's modulus of soil elasticity (assumed to be of the order of 50,000 kg/cm^2) in conjunction with the optimization of the location of the center of gravity of a tractor was, however, limited because the

use of "elasticity" values for "soft ground" crossing have little application. Young's modulus is, however, used for turf soils, in conjunction with evaluation of sinkage and motion resistance, for loads below the critical puncture values (Bekker, 1969).

Part of the second chapter of "Voprosy..." (1961) is entitled "Friction and Cohesion in Soils," and was written by Matsepuro and Selitskii. The authors introduced unorthodox concepts on the nature of friction and cohesion in soils by Prof. Pokrovskii (Coulomb was not mentioned), and used modified Troitskaya's (1947) concepts as a basis for calculation of soil thrust H for a tracked tractor, with a uniform load distribution:

$$H = pAtan\varphi \frac{e^{k_{PT}\lambda} - 1}{e^{k_{PT}\lambda} - ptan\varphi} + p\mu_o A' \qquad (40)$$

where μ_o is coefficient of friction between steel and soil; A is the ground contact area; A' is the area of spud tips; k_{PT} is a compounded exponent of soil value based on Pokrovskii-Troitskaya soil values (see equations 21 to 23).

Equation (40) contains three soil values: φ, k, and μ. In order to determine k_{PT} one must know the vertical deformation λ of soil per unit of the height of the soil prism under compression (equations 21 to 23). Although in a numerical example that deformation was assumed equal to 0.3, the practical method for measuring this number remains unknown to this writer. Since Guskov and others later used a different equation, it appears that formula (40) has a historical value.*

Chapter III of "Voprosy..." was written by Matespuro and Runtso (1961). It was concerned with ploughs. At the outset the authors state that "mechanical properties of soil are determined (for the study of plough draft only) by means of a special apparatus built by the Institute of Mechanization and Electrification of Agriculture," which consists of a cone penetrometer with three different tips. It is most interesting to note that the analysis of force spent on cone penetration was based on the $p = kz^n$ equation, assuming

* Equation (40) does not appear consistent, dimensionally.

Bernstein-Letoshnev k and n values. As a result the force p required to penetrate the soil to depth z was calculated in the following form:

$$P = 2\pi k_{co} \sin^n \left(\frac{\alpha}{2}\right) tg \left(\frac{\alpha}{2}\right) \left[tg \frac{\alpha}{2} + \mu_o \right] \frac{z^{n+2}}{n+2} \tag{41}$$

where k_{co} is a "coefficient of proportionality," α is the cone angle, and μ_o is the coefficient of friction; n is exponent of sinkage of the Bernstein-Letoshnev equation. In order to determine the three "soil values," k_{co}, μ, and n, three measurements of P must be performed with three different cones. The dimensions of the cones used by the Institute are shown in Table 12.

Table 12

Cone No.	Height of Cone mm	Angle α of Cone (^{o})
1	40	30
2	40	40
3	20	30

The three soil values can be determined from equation (41) (in which cone dimensions from Table 12 were properly substituted) with the help of three tests, each measuring forces P_1, P_2, and P_3, respectively:

$$\mu_o = \frac{0.754^n \times 18 - 33\,(P_1/P_2)}{91\,(P_1/P_2) - 0.754^n \times 67} \tag{42}$$

$$k_{co} = \frac{p_1\,(n+2)}{2\pi \tan 15^o \sin^n 15^o\,(\mu_o + \tan 15^o)\,z_1^{\,n+2}} \tag{43}$$

$$n = 33\,[\log\,(P_1/P_2O\,] - 2 \tag{44}$$

Test results produced the following soil values:

Table 13

Soil	Moisture (%)	k_{co}	n	μ_o
Heavy clayey soil, stubble	13-16	13-20	0.5-0.7	0.55-0.75
Medium clayey soil, stubble	12-14	13-19	0.5-0.6	0.55-0.70
Sandy soil, stubble	11-13	7-8	0.4-0.5	0.4-0.6

The remarkable feature of three-cone technique for the purpose of defining three soil parameters resembles the two-test-bevameter technique introduced earlier by Bekker (1955, 1957, 1958, 1960), which was extended later to three-test-operation for non-homogeneous soils (Bekker, 1969), using flat plates instead of cones. Note, however, that the three-cone test was not thought to be of use for locomotion purposes.

Since the three-cone soil evaluation was published in 1961, one may suppose that the Russian method was at least partially inspired by the two-plate American soil value measuring technique. And it probably was inspired by the still continuing use of the single-cone penetrometer for soil trafficability measurement by the Waterways Experiment Station, never considered by the Russians for that purpose, as shown by available evidence.

The similarity, however, between cones and plates ends here. The three-cone test by the Institute of Mechanization and Electrification of Agriculture introduced the non-essential parameter μ_o of soil-metal friction, while still using k_{co} parameter, which besides the soil values reflects the changing magnitude of cone size. The bevameter two-(or three-) plate test does not consider μ_o, and instead of k_{co} introduces k_c and k_φ values, which for practical purposes are "true" soil values, not contaminated with plate size effect.

There is no sign that k_{co}, μ_o, and n, the three-cone soil values, have ever been used in prediction of plough draft or tractor pull, for they could hardly serve that purpose. Bevameter values k_c, k_φ, and n, however, were successfully integrated in the methodology of terrain-vehicle system evaluation. The three-cone meter of the Institute for Mechanization and Electrification of Agriculture was thus created only as a means of soil identification for agricultural purposes. This identification, of course, was more sophisticated than the one-cone soil identification performed for trafficability purposes by the Waterways Experiment Station, in the United States.

As stated repeatedly (see reference Bekker, 1969) the bevameter technique could use 2 or 3 cones instead of flat plates. But a glance at the tediousness and approximations of Janosi's (1959) mathematics converting the cone action into plate action (track, tire, and wheel ground contact areas are plate-like, not cone-like), and at the involved

Russian equations of the three-cone test, makes one wonder why he would so deliberately complicate the issue without any tangible payoff.*

The situation illustrates the differences between the Russian agricultural engineers (Minsk School), and the American automotive (Detroit's Land Locomotion Laboratory, NASA, Aerospace Industries) and civil engineers (Waterways Experiment Station). Those who are familiar with emotional capital of vested interests, national pride, and professional survival can undoubtedly find an explanation of such an irrational behavior of otherwise rational people.

The Russian automotive engineers were no exception in the slow acceptance of changes in the professional "know-how" brought up by their colleagues in agriculture. Vlasov and Kuperman (1961) totally ignored any soil identification or measurement when testing the newly introduced "rolligon" type tires. For them it was enough to list soils in which tests were performed as: "dry asphalt highway," "snow covered road," "country road," etc. Even moisture content was not recorded during the tests performed in the "spring-summer-fall-winter" seasons. Yet the differences, for instance, in speed reflecting the wear of particular tires, sometimes were reported with the accuracy of 1.5%!

Semenov and Armaderov (1961) followed suit. They accurately measured torques, sinkage, motion resistance, etc., with "rolligon" and standard tires. But the soils tested were merely defined as "wet clay," "untilled agricultural field," "dry sand," "snow," etc.

Bocharov et al. (1961) did similar work in snow. Their concern for terrain identification, however, was reflected in the quotation of temperature range (0^o to 5^oC) and Bernsteinian k_B-value (from 0.35 to 0.43 kg/cm^3) as well as the depth of snow cover (0.7 to 0.8 m). But Klochkov (1961), who was concerned with tire slip in soft soils, identified the latter as "hard o soft clay road" or "sandy road." Note that the articles by Semonov, Bocharov, and Klochkov appeared in the same automotive magazine (Avtomobilnya Promyshlennost) in the same year.

* At the TRW-ISTVS meeting in El Segundo, Calif., in 1970, Prof. R. Yong of McGill University flatly stated that plate use will always be simpler, even if cone technique is proven practical in design-performance predictions.

Armaderov and Semenov (1962) improved soil characterization in the second article on tire testing. Here, they quoted "agricultural soil" with 15 to 20% moisture content, Plot No. 1 (proving ground of NAMI); sand, moisture content 2%, Plot No. 2; fine grained dry snow, specific weight 0.343 gr/cm^3, depth 30 cm., Plot No. 3; dry, ice covered asphalt, Plot No. 4, etc. The inconsistency of the value system was obvious, indicating that the Russian agricultural engineers apparently mastered the automotive approach better than their colleagues of the automotive profession.

This lack of consistency was striking to the Russian automotive engineers, too, for in April 1962 their leading magazine "Avtomobilnya Promyshlennost" featured an unprecendented six-page translation of the series of articles by Bekker (1959-1960) published in "Machine Design" and later republished as a brochure by the same magazine. Both the translation by Frenkin (1962) and the reproduction of essential drawings were concise and comprehensive.

Here, for the first time, American soil value system based on bevameter techniques was publicly presented to the Russian automotive engineers in their own language. Obviously, the reaction and results could not be assessed immediately. These will show up later, as discussed in the following chapters.

In the meantime the Russian work went as usual, which was not unusual. For the American automotive and agricultural engineers also took time to assimilate and use the new approach to the problem as old as the automobile. Thus, further work on "super" tires in snow, by Silukov (1962), only recorded the depth of the snow cover. However, here the author went one step further and reported changes in snow density with inflation pressure of the tire.

Some new ideas came with the publication of a paper by Rokas (1963). Although the paper was published in the Avtomobilnya Promyshlennost, Rokas' original study appeared in 1960 in a magazine devoted to design and construction of road building machinery (Stroitelnoye i dorozhnoye mashinostroenye). Judging from article annotations, Rokas was an Assistant Professor of Lituanian Institute of Technology in Kaunas.

Apparently he realized the basic two-directional character of soil loading under vehicle action, because he proposed another totally empirical index which could be related to the performance of the given vehicle in the given soil, by trial and error. But the

novel feature of the proposal was that Rokas (1950) equipped his cone penetrometer with vanes, and measured both penetration load and twist torque, instead of penetration only. Thus the empirical correlation had to be performed for two indices instead of one, which "per se" was more sophisticated than the American "cone" method.

The idea will be described in more detail in Chapters III and IV. At this time it may be noted that a similar concept was briefly entertained by Bekker (1945), who proposed "mobility index" measured by two plates simulating the track-plate shape and motion, under the simultaneous vertical and horizontal loads, and soil deformation.

This idea was rejected in 1945 by the Waterways Experiment Station which has always favored the single non-recording cone penetrometer. The idea was revived and rationalized ten years later, by the Land Locomotion Laboratory in Detroit, in the form of the bevameter technique. The new techniques attracted rather prominent attention by the Russian automotive and agricultural engineers (Frenkin, 1962), although they never dwelled on the "cone index."

The pulverization of efforts in defining machine-soil interface in terms of meaningful soil parameters may be found not only in Russia but also in other East European countries. Selected articles of the Polish Agricultural Journal contain, for instance, a paper by H. Bernacki (1960) which was based primarily, if not exclusively, on Russian and East German references, dated from 1954 to 1956. But for a change the author was concerned with a penetrometer test, using at least five different penetration plates which measure some sort of "soil compactness" and "mean compactness" in kg/cm^3. Significantly no cone was tried.

Closer scrutiny shows that Bernacki used Bernstein-Letoshnev k and n = 1. In oder to produce a number of different k's for different plates the author tabulated all the data as shown in Table 14, apparently leaving the right choice of the right k to the reader. To complicate the issue, repetitive loads were tried as well as time load-penetration tests. This led to the re-formulation of the need for full size test plates.

Even Soltynski's work (1962) published in Poland two years later did not change this picture. He departed radically, however, from this technique five years later, when he introduced the American system of soil values established by the Land Locomotion Laboratory, as will be discussed later.

Table 14

Soil	Plate f	Pressure Q	Unit Pressure q	Depth of Plate Penetration h	Soil Compactness (qo)	Mean Compactness of Soil (qo) med kg/cu cm
	sq. cm	kg	kg/sq cm	cm	kg/cu cm	
Medium-compact, well loosened; relative moisture content 60%	Plate A 4x5.6 = 22.4 sq cm	3	0.134	0.38	0.35	0.325
		5	0.223	0.73	0.31	
		10	0.446	1.37	0.32	
		13	0.581	1.79	0.32	
I	Plate B 1.9x13.8= 26.9 sq cm	3	0.112	0.34	0.33	0.317
		5	0.186	0.60	0.31	
		10	0.372	1.17	0.32	
		15	0.557	1.80	0.31	
	Plate C 5.5x7.05= 38.8 sq cm	3	0.077	0.26	0.30	0.306
		5	0.129	0.41	0.31	
		10	0.258	0.84	0.31	
		15	0.387	1.25	0.31	
		20	0.516	1.71	0.30	
Medium-compact soil, lightly settled after previous thorough loosening; relative moisture content 60%	Plate A 22.4 sq cm	5	0.223	0.26	0.86	0.88
		10	0.446	0.50	0.89	
		15	0.669	0.76	0.88	
		20	0.892	1.03	0.87	
		25	1.115	1.25	0.89	
		35	1.561	1.77	0.88	
	Plate B 26.9 cm	5	0.186	0.20	0.93	0.92
		10	0.372	0.39	0.95	
		15	0.557	0.62	0.90	
		20	0.444	0.83	0.90	
II		25	0.929	1.00	0.93	
		35	1.301	1.43	0.91	
	Plate C 38.8 sq cm	5	0.129	0.14	0.92	0.94
		10	0.258	0.26	0.99	
		15	0.387	0.43	0.90	
		20	0.516	0.53	0.97	
		25	0.645	0.70	0.92	
		35	0.903	0.96	0.94	
	Plate D 2x5=10 sq cm	3	0.3	0.32	0.94	0.91
		5	0.5	0.54	0.92	
		10	1.0	1.13	0.89	
		15	1.5	1.70	0.88	

In the meantime an agricultural engineer named Shavlov (1963) was faithful to the Bernsteinian k_B-value and to Bernstein-Letoshnev's solutions. But Skotnikov (1963) based evaluation of performance of track-laying tractors on turf, on Housel's "law" of area-perimeter ratio, with two soil parameters. He considered a two-layer structure, and for the evaluation of ground pressure under the catenary of track, he referred not only to the drawing and soil values but also the denotation by Bekker (1956).

However, Skotnikov's soil parameter k in equation p = kz, with which he started, was defined in terms of:

$$k_{SK} = \frac{S_o}{\eta_S \sqrt{A}} \tag{45}$$

where $S_o = E/(1 - \nu^2)$. E is the modulus of turf elasticity measured in kg/cm^2; ν is Poisson ratio; and η_S is a coefficient which takes care of the shape of the load bearing area A (kg/cm^3).

Inelastic soils were treated in accordance with Bernstein's soil values. To this end, Bocharov et al. (1963), concerned with automobile tires riding on a soft field in spring time, measured k with Revyakin's plate penetrometer; the load-penetration curve then had the following form:

$$p = 2.1\, z^{0.5} \tag{46}$$

i.e., k = 2.1 and n = 0.5. However, these soil values were used to define the state of the ground rather than tire performance. The lack of a recognized theory of pneumatic tires was apparent here, in spite of Omelianov's (1948) and Ageikin's (1959, 1960) pioneering efforts.

Even a year later, Bocharov (1964) and his group were more concerned with tire-behavior "per se" than with soil-tire interface, as if the latter had little effect upon performance. Again, theirs was an empirical exercise concerned with tire deflections and static and dynamic tire radii. But somewhat spurious was the conclusion that tire internal losses on hard and soft ground are different.

This work represented quite well the automotive school of thought and its activity around the year of 1964. Agricultural engineers, however, particularly those related to the influential Institute of Mechanization and Electrification of Agriculture in Minsk,

were further taking a more serious approach. They were concerned with substantial soil deformation when ploughing and tilling, so the soil-machine interface could not be easily treated by simple empirics. Volume 13 of "Voprosy Selskohozyaisvennoi mehaniki" (1964) (Problems of Agricultural Mechanics) brings again the notions of viscoelastic soil parameters (Maxwell), and theories by Goryachkin who based much of his work on Mohr's theory of soil failure and parameters c and φ. Work by Terzaghi (1943) also was stressed. Bernstein-Letoshnev's soil values, k, n, including Saakyan's (1959) k_s and dimensionless deformation measure, z/d, (where z is plate sinkage and d plate diameter) were referred to. Soil values k and n were quoted in detail (see Table 8). Also soil values by Troitskaya (1947), Korchunov (1948), and Aziamova (1957), including the fitting of load-penetration curve by hyperbolic tangent function, were reported as previously described. Discussion of tire resistance by Guskov, Kuzmenko, and Badalov (1964) led to equation:

$$R = \frac{1.13^{\frac{2n}{2+3n}}}{(1+n)\left(1-\frac{n}{3}\right)^{\frac{4+3n}{2+3n}}} \; \frac{W_o^{\frac{4+3n}{2+3n}}}{k^{\frac{2}{2+3n}} \, b^{\frac{2-n}{2+3n}} \, D_R^{\frac{2+n}{2+3n}}} \tag{47}$$

attributed to Knoroz (1960).*

A comparison of equation (47) with equation (48) proposed earlier by Bekker (1957, 1960) for a rigid wheel:

$$R = \frac{3^{\frac{2n+2}{2n+1}} \, b^{\frac{1}{2n+1}}}{(3-n)^{\frac{2n+2}{2n+1}} (n+1) k^{\frac{1}{2n+1}}} \; \frac{W^{\frac{2n+2}{2n+1}}}{D^{\frac{n+1}{2n+1}}} \tag{48}$$

shows numerical differences stemming only from differences between a tire, rigid wheel, and other assumptions. For instance, k_s is the Saakyon soil value; the value of W_o is quite involved:

$$W_o = W - \frac{2}{3} c_t b \, \Delta \sqrt{D \Delta} \tag{49}$$

* The referencing of this chapter was, in all probability, erroneous, and Knoroz's work was not available.

where W is tire load. The value of c_t was calculated from equation:

$$c_t = \frac{2W}{\pi \Delta^2 \sqrt{Db}} \quad (50)$$

Finally, the "relative" tire diameter D_R was defined as:

$$D_R = \frac{(c_t + k_B) D}{c_t} \quad (51)$$

where k_B was Bernstein-Letoshnev modulus of soil deformation and n exponent of load-deformation curve.

Thus the soil values used in this semi-empirical tire-terrain evaluation were k_S, k, and n. Numerical values presumably measured for a 12-38 Goodyear tire were given in Table 15.

Table 15

Soil	k_S kg/cm^2	k_B kg/cm^3	n
Ploughed field	0.8-2.5	0.4-0.8	0.4-0.5
Soil ready for seeding	2-4	1-2	0.45-0.55
Stubble	3-8	4-6	0.55-0.65
Virgin soil	7-15	5-10	0.60-0.80

What was most significant was the structural similarity of equations (47) and (48), and of the soil values k_S, k_B, and n, where it may be assumed that $k = k_c/b + k_\varphi$. This similarity was further enhanced by Guskov, Kuzmenko, and Badalov (1964) by the definition of the shearing strength of the ground by Coulomb's equation:

$$\tau = c + p\tan\varphi$$

The advanced thinking of these investigators was reflected, but only to a limited extent, in a publication describing the proving ground facilities of the Odessa Scientific Research Station, and Automobile and Tractor Scientific Research Institute (Shchupak and Makarov, 1964). The description of how the concrete, clay, sand, and soil test tracks were built referred only to soil processing and moistening for the purpose of keeping

shearing strength constant. No other soil values, however, were mentioned besides "hardness" defined in kg/cm^2. Clay was described in terms of plasticity index and liquid limits because of the existence of an enormous span of possible uncontrolled variation of mechanical properties. No references to other work was given, except for casual reference to "similar test results" recorded at tractor proving grounds in Wagenengen (Holland), Nebraska (U. S. A.), and Wiselburg (Austria).

On this background one may understand why mechanical engineers concerned with machine design did not pay much attention to soil. But when investigating motion resistance and thrust of pneumatic tires, they were meticulously accurate to define mechanical structure of the tire and the inflation pressure. Filyushkin (1964) represented that approach in an experimental testing of 6x4 trucks equipped with different tires. His tests were performed on meadows, arable soil, and sand. Soil "values" used were described as follows:

- depth of organic layer 30 to 40 mm with moisture content of the underlayer 4 to 6%
- arable soil, moisture 17 to 20% with "hardness" of 1.3 = 1.5 kg/cm^2
- sand, dry, loose moisture 2.5 to 3% depth of 300 mm; density 1.6 gr/cm^3; particle size 0.25 to 0.63 mm more than 60%.

Conclusions reached, in respect to tire performance, applied, of course, to the above defined soils, and could hardly be generalized over other soils because of lack of the definition of mechanical properties of the ground.

A similar approach was followed by Kudinov (1964) of the Ukranian Academy of Agricultural Sciences. When measuring traction of tractors in a turn, he defined the soil in the following manner:

- gray and sandy
- moisture in the top layer 5 to 10 cm amounted to 12.5%; in the lower layers, 15 to 20 cm thick, amounted to 14.02%
- "load resistance" measured with the meter SKB, of MGU design amounted to 29.3 kg/cm^2.

This amateurish treatment of the problem was in contrast with work by Strokov (1964), based on an ingenious hypothesis by Academician Zheligovskii, which was confirmed by Asanov (1962) and the others.

Zheligovskii presupposed that the optimum rolling resistance of the pneumatic tire is defined by the point of equality of work spent for tire deformation and the work spent on soil deformation. Obviously, measuring the work spent on soil deformation necessitated introduction of soil values. Thus Strokov (1964) used Omelianov's (1948) theory (see equation (33)) with soil parameters k and n. Practically the same thing was done before in the United States with k_c, k_φ, n parameters (Bekker, 1960). Thus the discussed Russian work seems to have enhanced the soil value system based on Bernstein-Letoshnev-Bekker methodology.

Automotive engineers Armaderov et al. (1964), however, did not show much interest in Zheiligorskii's, Strokov's, and Omelianov's soil value definitions, and further followed Kudinov, using only qualitative soil descriptions such as:

- agricultural soil
- sand
- snow
- asphalt
- wet clay road
- road covered with fresh snow to a depth of 350 mm.

What generalized merit the measured vehicle performance could have under such ill-defined soil conditions, is obvious. Surprisingly, the work was performed under the auspices of NAMI (Scientific-Tech. Inst. for Motor Vehicles).

Paradoxically, the Central Research Institute for Mechanization and Efficiency of Forest Industry (RSFSR) was providing, at the same time, snow measurements in Bernstein-Letoshnev values k, in gr/cm^3 (Karelin, 1964):

Surface snow (depth 7 cm)	$k = 0.25\ gr/cm^3$	Temperature: -11 to -17° C
"Sugar Snow"	$k = 0.27$ to $0.31\ gr/cm^3$	
"Old Snow"	$k = 0.31\ gr/cm^3$	

A year later a member of VISKHOM (All Union Res. Inst. for Constr. of Ag. Machinery) published description of sophisticated instrumentation for measuring physical-mechanical properties of soils (Vysotskii, 1965).

The instruments (which will be described in Chapter IV) recorded depth-resistance curves of a penetrometer, and the coefficient of friction between metal and the soil. But if it is realized that recording the penetration resistance with depth was practiced (for other purposes) since Bernstein (1913), then the progress made by Vysotskii was not significant. Soil-metal friction also was repeatedly investigated in plough studies.

At the same time, however, Rokas' idea of recording arbitrary soil indexes by means of a probe which rotates when penetrating the ground (see reference Rokas, 1960) was revived. As an assistant professor at Kaunas Institute of Technology, Rokas (1965) published another paper in which he recognized the need for measuring soil cohesion c and friction φ, and accepted their Coulombian relationship, $\tau = c + p\tan\varphi$, as well as the "quick shear" test in a shear box or shear ring as proposed earlier in American works (Bekker, 1955, 1956). But he again expressed displeasure with the "cumbersomeness" and complexity of such tests, and continued to advocate his "cone-cum shear" method – this time with elegant mathematical analysis and alignment charts for determining soil friction φ and cohesion c. He did not seem to realize, however, that the dissimilarity between the forms, loads, and shear boundaries of his bladed cone, and the ground contact area of the vehicle, led to c φ values peculiar to his instrument's readings and were not of much use for vehicle performance and design evaluation. Identical misunderstanding has existed since World War II with the use of the so-called British shear vane and the WES cone penetrometer. To compound the arbitrariness of his indices, Rokas established the concept of the "specific resistance to penetration," which was defined by the load required to force the conical head of his instrument into the ground, divided by the cone base area; this was practically the same notion as that of the Waterways Experiment Station's "cone index" introduced in the U.S. around 1943.

This definition of soil values did not find an echo in Russian literature, and any application of the Lithuanian rotating "cone-blade penetrometer" and of the "specific resistance to penetration" remained unknown to this writer until it was briefly revived by Polyakov and Nafikov (1969). This revival, looks like an entirely sporadic event brought about

by members of an organization which, though interested in off-road mobility, has remained thus far unquoted by automotive and agricultural researchers. The organization was V. V. Kuibyshev Military Engineering Academy.

In the meantime, Armaderov et al. (1965) did not bother even with the existing soil parameters, when trying to define the economic regime of work for a 6x6 truck for NAMI. They simply used the following descriptive soil "values":

- dry sand
- wet meadow, etc.

This qualitative soil value definition for automotive purposes was in line with the definition of Armaderov's contemporary agricultural engineers in America, such as McLeod et al. (1966), who were interested in draft, power, efficiency, etc. of low pressure tires; they also spoke about:

- Hivasse sandy loam (M. C. 9.4 to 14.7%)
- Lloyd clay (M. C. 18.0 to 23.6%), etc.

quoting extremely accurate numbers related to tire performance versus thus defined soil types, as if "hivasse sandy loam" with 9.4% moisture content could have had any quantitative meaning.

However, their contemporary, Krasilnikov (1966), reverted to Bernsteinian soil values, k_B (kg/cm^3) and $n = 1$, when investigating cornering forces of an automobile at the Moscow Institute of Automotive Research (NAMI). And Kosharnyi (1966), who performed a similar study, based his calculations on Bernsteinian k_B, which was determined in situ by Revyakin's plate penetrometer. This penetrometer used plated equal in size and form to ground contact areas of the tires. The following soil values were recorded:

Table 16
(Revyakin Plate Penetrometer)

Soil Values	Dry Potato Field	Stubble	Wet Ploughed Field
$k (kg/cm^3)$	0.5 - 0.8	1.2 - 2.0	0.30 - 0.5
n	1.0	0.5	0.5
Probe Depth (cm)	1.4	6	6

Test data shown in Table 16 led to the determination of compaction resistance in much the same manner as that by bevameter techniques (Bekker, 1960). Unquestionably, Kosharnyi's work was based on Bekker's theory and soil value system, since the series of articles published by the latter in Machine Design (Bekker 1959-1960) as well as his earlier work (Bekker, 1956) were quoted in the references by Kosharnyi, including the reproduction of pertinent drawings.

Kosharnyi's study was performed and published under the auspices of the Ukrainian Institute of Mechanization and Electrification of Agriculture (UHIMESH). It is one of the rare scholarly analyses, with much accent on the theory. Soil values c and φ were considered in Coulombian fashion, including force-deformation diagrams, under the tire, following those by Bekker (1956, 1960) and Söhne (1957).

The American approach to soil-value definition, followed to a large extent by Kosharnyi, was accepted in Poland during the same period by Soltynski (1965) of the Institute for Mechanization and Electrification of Agriculture. In his Mechanics of a Terrain-Vehicle System, Soltynski mainly translated, paraphrased, and reproduced Bekker's work (1956, 1960) as well as that by his co-workers at the Land Locomotion Laboratory. Soltynski's impressive book was entirely based on the Bernstein-Letoshnev-Bekker soil value system $k_c, k_\varphi, n, k, c, \varphi$, and did not use any of the empirical "indices," both Russian (Rokas, Poliakov and Nofikov, etc.) and American (Waterways Experiment Station). It also neglected the Russian variants of soil values such as those proposed by Troitskaya (1947), Katsygin (1964), etc.

Soltynski's book thus became a vanguard of a rather broad and significant change in the philosophy of soil measurements, which may not have remained without effect on Russian work.

It would appear that the years 1960 to 1966 brought much clarification of the problem of soil parameters and contributed to a consolidation of the Coulomb-Bernstein-Letoshnev-Bekker soil value system.

This observation does not imply that various investigators have started using since then, the same mathematics for fitting the experimental load-penetration curves. But the fact that the Russian agricultural engineers definitely turned toward what they

be called the "bevameter" philosophy based on the use of Coulombian shear test plus the load-penetration plate test, both simulating the vehicular load conditions and the ground contact area, was most significant. While the American school of thought simplified the load-penetration tests by introducing plates smaller than the ground contact areas of the vehicle (Bekker, 1960, 1969), at the cost of some inaccuracy (which is experimentally definable in a soil bin), the Russian school preferred to use plates equal in size to vehicle's ground contact areas. Thus, conceptually, the difference between the Russian and American approach vanished.*

This strongly affected one of the most recent books on optimization of tractor parameters (Guskov, 1966), indicating that the plate penetration tests plus shear tests "in situ" became the only rational approach to the problem of prediction of performance and design parameters of terrain-vehicle system.

In the final analysis, then, the Russian agricultural engineers have established a school of thought in soil definition, while their automotive counterparts seem to be mainly preoccupied with hardware and descriptive empirics of soil-vehicle relationship (with the exception perhaps of Ageikin and Frenkin), though using occasionally Bernstein-Letoshnev soil values.

Also what is more interesting, from the American viewpoint, is the fact that Russian civil engineers played practically no role in this intellectual match. The excellent book by Zelenin (1950), devoted to the theory of ground cutting, covered some of the theoretical material elaborated by Bekker (1948), and added much practical information on soil machining, and on the measuring of soil resistance against penetration by static and impact penetrometers (these will be discussed in Chapter IV). Zelenin, apparently a civil engineer, quoted only locomotion studies by Letoshnev (1936) and Pigulevskii (1936, 1936 a), but he was not quoted by the students of agricultural or automotive engineering. Evidently the Russian civil engineers neither cooperated nor competed in solving the problem of soil-values for locomotion purposes.

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* Professor V. V. Guskov expressed that opinion during a meeting with this writer at the University of Newcastle-upon-Tyne, in 1967.

This was in a sharp contrast to our own studies in ground mobility and soil trafficability.

The Eve of Consolidation

Guskov's (1966) work, previously referred to in connection with the description of earlier concepts of Russian agricultural soil values (Vernikov, 1940; Korchunov, 1948; Troitskaya, 1947; Saakyan, 1953; Gutyar, 1955; Azyamova, 1959; Katsygin, 1964), is, in a sense, the first general methodological outline of ground mobility analysis, though much of the material contained therein was published before.* If his short book is an authoritative text for agricultural engineers, as it seems to be, there is little doubt that sooner or later it will be accepted in automotive engineering.

The Russian philosophy of measuring horizontal shear values c and φ, and vertical penetration values k and n, is based on tests with loading plates, preferably having the full size or a size close to the dimensions of the vehicle's ground contact areas. But the overwhelming variety of curve fitting and soil parameters undoubtedly called for some house cleaning. This was noticed in the most recent writings of the Minsk School, which selected Katsygin's (1963) method of fitting hyperbolic function into the experimental curves as a basis for its operations.

Curve fitting and arithmetics of horizontal shear values c and φ, and their mathematical relationship with shear strength, have never been seriously questioned by anyone since their introduction in land locomotion (Bekker, 1948, 1960). Perhaps the 200-year old authority of Coulomb lent its support for that purpose. But the vertical penetration values k and n (or k_c, k_φ, and n) were subject to mathematical manipulations since they were first proposed (Bernstein, 1913; Letoshnev, 1936; Bekker, 1955) by practically anyone who tried to fit still another function into the set of experimental load-sinkage curves.

Thus the fitting of such curves with a hyperbolic tangent function by Katsygin, Guskov, and the others, instead of with an exponential function of Bernstein-Letoshnev-Bekker

* Primarily in the volumes of "Voprosy Selskokhozyaistvennoi mekhaniki" (Problems of Agricultural Mechanics).

type, is no surprise, particularly if it is realized that tanh also is an exponential function:

$$\tanh \alpha = \frac{e^{\alpha} - e^{-\alpha}}{e^{\alpha} + e^{-\alpha}} \tag{52}$$

Thus, in fact, the Russian effort of creating their own soil-values and their own method of computation really was not a significant departure from the common path first traced by Bernstein.

Since the Russians followed the Bernstein-Letoshnev concept (k, n), using full size loading plates of the soil testing instrument, they did not need the small size two-plate bevameter set, and the three soil values (k_c, k_ϕ, n). Only two of them conceptually similar to k and n were totally sufficient, and one large plate was enough. The new form of the "soil value" equation was thus fixed in a hyperbolic tangent function:

$$p = p_{KA} \tanh \left[\frac{k_{KA}}{p_{KA}}\right] z$$

as discussed in equation (24). The soil parameters replacing k and n have different structure and connotation here, but the empirically measured curve is the same.

The reasoning by means of which the Russian school replaced the exponential load-penetration equation with a hyperbolic function shown above was developed by Katsygin (1964). The author started with writing a differential equation for the load-penetration curve, which when integrated produced a hyperbolic tangent. Obviously, a similar process could have produced an exponential function, even in a simplified Bernsteinian form. The whole operation appeared superfluous, since curve fitting is more of an intuitive, heuristic nature than of a rigorous rationalization of the complex and elusive process of soil penetration.

Guskov fully realized the deficiency of the Russian method stemming from large test loads, large soil testing instrument, and from the impossibility to generalize the soil values as such. He expressed his views both to this writer personally and in his book. In the latter he proposed replacing k_{KA} with another k-value, as shown in equation (26), in order to eliminate the plate size effect, and to enable one to use the smaller instrument.

As it results from American work (Bekker, 1960), such a solution may be practical (with definite restrictions) only in those cohesive soils where $k_{\varphi} = 0$, i.e., in fat, plastic clays. Whenever strong frictional modulus of deformation k_{φ} exists, Guskov's solution does not work. He was aware of this.

What are the most recent developments in this respect, no one can tell because of lack of information. However, in one of the recent letters addressed to this writer, Professor Guskov (1969) expressed this view this way:

> "I think that the problem of a more generalized soil value system which is independent of the size of the loading area is very interesting, and now we try to do something in this direction."

For the definition of thrust Guskov quoted Bekker's 1956 equation in its original form:

$$\tau = \frac{K_3}{2K_1\sqrt{K_2^2 - 1}} \left[e^{(-K_2+\sqrt{K_2^2-1})K_1 j} - e^{(-K_2-\sqrt{K_2^2-1})K_1 j} \right]$$

But he also expressed a dissatisfaction with the equation: "irrespective of the agreement of this formula with some actual soil load-deformation processes, it cannot be applied to the calculation of relationship of the tractor pull and soil because of a number of important deficiencies." These "important deficiencies" were explained in terms of:

- complexities of equation structure
- difficulty of its computations, and the
- physical lack of meaning of the formula for $K_2 < 1$.*

All this seemed but an excuse for quoting Pokrovksii who proposed a slightly different form of the shear equation:

$$\tau = (c_1 e^{-c_2 j} + c_3)(1 - e^{-c_4 j}) \tag{53}$$

* It is obvious that many empirical equations have practical values within a certain interval of the variables – a fact recognized by Guskov in his work but not in reference to the discussed equation.

It is noteworthy, however, to stress that Equation (53) is in essence the equation for loose granular or plastic soils, as proposed in the United States by Janosi and Hanamoto of Land Locomotion Laboratory (1961):

$$\tau = (c + p\tan\varphi)(1 - e^{-j/K}) \tag{54}$$

But even equation (53) was criticized by Guskov to the effect that it fits poorly into extreme experimental data (which have little, if any, practical application). Hence, he expressed a preference for the shear equation by Katsygin (1963):

$$\tau = p\mu_m \left[1 + \frac{\mu_{KA}}{\cosh\left(\frac{s}{k_\tau}\right)} \right] \tanh\left(\frac{s}{k_\tau}\right) \tag{55}$$

where all the values were defined in equation (30). Again, one should not argue if an exponential function in Bekker's equation is better than a hyperbolic function in Katsygin's considering that:

$$\cosh(\alpha) = \frac{2}{e^{\alpha} - e^{-\alpha}} \tag{56}$$

The subtleties of the merit of curve fitting are so subjective, when compared to the practicality of results obtained, that the matter of soil values may be left to the preference of the investigator. Depending on the breadth of his approach to ground mobility, he will soon find if the mathematical niceties which fit neatly in one spot, make sense in another.

This question cannot be momentarily resolved, since the Russian approach, equation (55), is not known to be as widely used as the Coulombian's theory of shear is used in America. In any case, the μ_m and μ_{KA} values of equation (55) are a mixture of Coulombian c and φ values, with the latter entering specifically in the form of $\mu_m = \tan\varphi$. Interestingly enough, shear deformation s enters in a slightly different form in both the Russian and the American equations, although the philosophy of defining soil values in shear is the same in both approaches.

The closest follow-up of American approach was found, in this area, in the work by Grecenko (1967) of the Czekhoslovak College of Agriculture in Prague. He adopted Coulombian soil values for thrust calculation and re-interpreted his "binomic"

slip-thrust equation in terms of c, φ, and K values, as originally postulated by the Land Locomotion Laboratory's work for soil strength and slip.

This study was a perfect example of the evolutionary development of the existing theory and its variants, through the new interpretation of results, in a modified context. Whether that led to a better, faster prediction of soil thrust is open for discussion. In any case Grecenko's method was limited to "predominantly frictional soils," in contrast to the more generalized American method (Bekker, 1956, 1960).

The consolidation of ideas for soil-value measurements inevitably led to more specialized studies such as the effect of speed of the deformation upon soil resistance. The complexity of the problem was readily recognized. Podskrebko (1967) approached it from the theoretical viewpoint, stressing the lack of experimental data. His study was again based on Maxwell's equation of stress relaxation (see Bekker, 1956). Experiments performed between 1960 and 1962 produced semi-empirical equations for time-compression stress; the equations contain speed of deformation (cm/sec), modulus of soil deformation (kg/cm^2), and the time of relaxation obtained from an idealized soil sample.

The solution does not seem to have a direct practical application, because of the lack of knowledge of stress distributions and boundary conditions of soil-machine interfaces, as well as because of the inadequacy of Maxwell's model. In a similar category were found tests by Vinogradov (1968) on the dynamic strength of soil. Laboratory results of axial sample loading did disclose an increase in failure stress, but so slight that it could be neglected in most cases. This was discovered a long time ago by the Land Locomotion Laboratory, in Detroit.

These academic rather than engineering studies led to the inevitable step of defining the modulus of soil deformation and the Poisson ratio (Podskrebko, 1967 a). With due credit for the fine review of the state of the art, Podskrebko's work did not go beyond the early stages of soil mechanics (Bekker, 1956), which had little, if any, practical effect upon the solution of engineering problems. This course of action, however, was inevitable. The work by the U. S. Army Land Locomotion Laboratory went through a similar search in the early and mid-fifties, and it is not surprising that the Russians tried the same.

Besides Podskrebko (1967, 1967 a) who represented agricultural engineering, Glagolev and Poletayev (1967) from the Moscow Automotive Institute also tried Maxwell's relaxation model and attempted to obtain a solution for the wheel, which was based on the ephemeral soil modulus of deformation and soil relaxation time.

In contrast to these attempts Melnikov (1966) of the Central Institute of Mechanization and Electrification of Agriculture of Non-Chernozem Zone of the U. S. S. R. used elaborate plate penetration tests for turf, which were fitted with the Katsygin-Guskov hyperbolic function of load-sinkage (see equation 24), and with the empirical equations of speed effect upon that function. The speed effect was based on the assumption that:

$$\left.\begin{aligned} p_{KA} &= p'_{KA} + c_v v^2 \\ k_{KA} &= k'_{KA} + mv^2 \end{aligned}\right\} \qquad (57)$$

where c_v and m were empirical coefficients; p'_{KA} and k'_{KA} were Katsygin's soil values (equation 24) at speeds v of penetration close to zero. Melnikov also suggested that p'_{KA} may be expressed by means of Housel's (1929) formula (equation 18):

$$p_{KA} = A_o + B_o \frac{U}{A}$$

Guskov (see "Trudy" 1969) followed this procedure.

In the meantime, further crystalization and consolidation of some sort of a soil-value system, for practical purposes, was expanding beyond the boundaries of the U. S. S. R. The previously quoted Polish book by Soltynski (1965) was followed by an excellent Hungarian book by Sitkei (1967), who quoted Bekker's soil values extensively (1956, 1960), and the values by Saakyan (1953), Katsygin (1964), and Reece (1965). Bernstein-Letoshnev and Coulomb concepts, which underlie the bevameter technique, were used often for elaboration of various aspects of agricultural technology. The absence of discussion on arbitrary "coefficients" and "cone indices" was striking.

The scholarly work by Sitkei even fancied the treating of soil flow under the cultivating blade by means of Bernouilli's equation, in an attempt to generalize some of Goriatchkin's solutions for agricultural purposes. The use of dimensional analysis, following work by

Hegedus (1965) of Land Locomotion Laboratory in Detroit, and embracing Bernsteinian k and n-values, was a further example of an attempt at rationalization of the mechanics of soil-machine relationship.* Bekker's solutions for tracks and wheels (1956, 1960) were elaborated upon in terms of bevameter soil values, and the classification of trafficability of soils in terms of k_c, k_φ, n, c, and φ was referred to in detail. One may wish that Sitkei's excellent book were made available in English.

Soltynski's (1965)** book was used, in the meantime, in various practical applications, apparently with success. An analysis of a screw driven vehicle based on bevameter soil values (Soltynski, 1967) was tested experimentally in a soil bin and in the field, and led to the formulation of design requirements, as well as determination of the error involved in theoretical predictions.

Some of the Russian agricultural engineers, however, still considered soil density (kg/cm^3), and ground hardness (kg/cm^2), when investigating soil compaction by wheels in relation to tracks (Makarets et al., 1967).

This hardness definition was not given, although it may be surmised that it meant a mean penetration load of the Revyakin flat plate penetrometer, measured at specific depth ranges and moisture contents. This specialized type of investigation was not closely related to the broader definition of soil values for locomotion purposes.

Empirical equations for tractive efficiency of various tractors, deduced statistically by Velev (1967) from tests made with 36 track and 3 wheel tractors at a Bulgarian test station, also were still based on primitive soil values merely described as "stubble with normal soil moisture and hardness," This seems to indicate that while the Russian, Polish, and Hungarian work showed a maturing trend, Bulgarian studies were speculative and empirical since they lacked well defined soil parameters.† The significance of this work has more of a methodological meaning for tractor design "per se" than

* Sitkei seems to be the first to seriously contemplate dimensional analysis. But his interests were much broader and did not encompass locomotion alone.

** Soltynski's book has been translated and distributed by the International Society for Terrain-Vehicle Systems.

† A similar conclusion was drawn from the perusal of scarce Roumanian work by agricultural engineers.

for considering soil definition in evaluation of traction efficiency, which reflected the spirit of the Nebraska tests.

But Guskov (1967) continued to implement the soil values, as previously described, in terms of hyperbolic functions. In a study devoted to the optimization of weight distribution of tracked vehicles he made full use of the analytical method based on p_{KA}, k_{KA}, k_{τ}, μ_m, and μ_{KA} as defined in equations (24) and (55). The paper was based on his previously published book (Guskov, 1966), and was subsequently presented in England in a number of lectures.

When it came to consider snow going vehicles, the Russian agricultural engineers did not have a clear picture of the mechanical properties of snow. They resorted to direct measurements of vehicle performance without a strict definition of snow values (Klochkov, 1967). The latter were again measured in terms of crystal size and atmospheric temperature. But a coefficient, k_v, was used to define the increase of "static bearing capacity load," p_o, with sinkage z of a penetrometer plate forced into the ground at a constant speed, v (cm/sec). Thus the compaction resistance R, which was recognized after Bernstein-Letoshnev to be the main component of motion resistance, was expressed in the following form:

$$R = ab \int_0^z p_{ov}\, e^{k_v \epsilon}\, dz \qquad (58)$$

where b (cm) was the width of the track, and ϵ was the ratio of the depth of penetration of the measuring plate to the depth of snow cover.

In spite of somewhat different mathematics of curve fitting and snow "parameterization," the Bernstein-Letoshnev-Bekker structure of R is obvious in equation (58). Note the stressing of the speed of snow deformation v; special care was taken to translate it in terms of tractor speed. The work was based on experimental studies by Krizhivitskii (1950), and Rukavichnikov (1957); the 1966-1967 contributions of the Minsk School were not referred to (see equation 359).

This approach probably was a res[illegible] the old studies by Richter (1945), Kragelski, Kondratyeva, Shakhov, and other[illegible] nsson Library, 1948 and Bureau of Yards and Docks, 1949), who measured snow-penetration curves by means of a flat plate,

together with the corresponding density change. Even in these studies, however, the motion resistance of snow compacting rollers and the pressure they exercised were identical in form with Bernstein-Letoshnev equations for a rigid wheel.

The old idea of Brinell hardness, however, was deeply embedded in the Russian school of snow studies (Kragelskii, 1945), which is not surprising when considering that snow, unlike the soil, is the source of more severe and more differentiated problems. But it is worthwhile to note that Kragelskii performed around 1945 what may be called the first bevameter tests by using different plate sizes of 3x3, 5x5, 10x10, and 20x20 cm.* He also referred to the Swedish tests by means of cones which were used in different shapes with angles of 30, 60 and 90 degrees; the rather intangible and variable coefficient of friction between the cone and the snow was the source of Kragelskii's concern. Relaxation time of snow also was of great interest to him. In the final analysis, however, Bernstein-Letoshnev's concept of roller motion resistance was used. and the idea of snow friction and cohesion was introduced.

The scholarly work by Kragelskii must be recognized, indeed, as the earliest precursor of soil-snow measurements, which subsequently led to modern techniques of plate penetration tests and the interpretation of soil-snow values in terms of hyperbolic functions in the U. S. S. R, and to the bevameter tests used in conjunction with exponential functions in the U. S. A.

Interestingly enough, Klochkov's (1967) approach to measuring snow parameters with a flat plate load-penetration test, equation (58), was again used by Yankin (1968), and was recommended for predictions of compaction motion resistance of a snow roller. Experiments with speed effect, of course, were made in order to enable one to use equation (58). Verification of the analytical and experimental methods related to plate penetration tests was found to be entirely satisfactory.

The beginning of crystalization of concepts of soil and snow measurements is perhaps most clearly visible in the first chapter of a book on cross country vehicles published by the editors of Mashinostroyene. This book summarized and critically reviewed the

* The interpretation of results was different from the bevameter technique.

state of foreign and domestic arts for the benefit of automotive engineers. In a sense, it is a synthesis of work by agricultural and automotive engineers. Interestingly, this work does not contain any reference to any contribution by civil engineers. The book is a collective work written by Grinchenko et al. (1967). In the first chapter it deals with vehicle ground mobility; in the second, with design of cross country vehicles; in the third, with analysis of foreign cross country vehicles; in the fourth, with transmissions; in the fifth, with basic chassis components; in the sixth, with controls and steering; and in the seventh, with exploratory and "revolutionary" foreign vehicle concepts (articulated vehicles).

This represents a typically balanced exposition of vehicle R&D, where soil is only a small part of vehicle development, and is overwhelmed with mechanical engineering rather than with soil mechanics problems. Thus the book does not refer to the professionals or organizations primarily concerned with foundations, highways, tunnels, dams, or flood control.

A brief review of ground mobility chapter is of singular interest in the present analysis. The story does not start with tri-axial tests, "cone penetrometers," or other standard civil engineering practices, which have been typical of a segment of American papers on vehicle mobility. None of these papers though widely publicized in a number of articles (SAE and ASAE presentations), and particularly at the International Symposium held in Italy (First Int. Conf. on Terrain-Vehicle Systems 1961), were referred to by Grinchenko, with one exception which will be discussed later.

The first chapter was written by S. G. Volski, and critically reviewed by Dr. Eng. A. K. Frumkin, under the general editorial supervision provided by Prof. Ya. S. Ageikin. The chapter starts with Coulombian soil properties φ and c for traction τ definition: $\tau = p\tan\varphi + c$ and with Bernstein-Letoshnev-Bekker properties k and n for motion resistance and sinkage z: $p = kz^n$.

Bernstein-Letoshnev equations of wheel resistance and sinkage were quoted for various n-values. Extensive discussion of the ramifications involved in pertinent equations also was made available. Analysis of the effect of various peculiarities of wheel design was included in the discussion, stressing the automotive aspect of soil values rather than soil-mechanics "per se." For the purpose of description and identification of

standard test courses, their grain size distribution, moisture content, and plasticity index, in addition to k, n, c, and φ, were listed. Snow strength was measured in the the same manner as that of soil. Soil bin techniques were briefly discussed. A rather generalized formula attributed to Babkov (1956 a) was quoted for vehicle "passability" of the given terrain. This formula, when fed with Bernstein-Letoshnev soil values, was identical to Bekker's solution (1956, 1960), which states that slope i_s may be overcome if unit soil thrust H/W minus unit motion resistance R/W is larger than i_s:

$$\frac{H - R}{W} \geq i_s \tag{59}$$

where W is the load supported by the driving vehicle elements.

In a discussion of American measures of vehicle passability the author observed that the "cone index" of ground mobility by Waterways Experiment Station (WES) is empirically "linked with the indications of a penetrometer — a device which measures resistance of terrain by means of impressing a conical head." Volski also mentioned that Rokas (1960, 1965) and the others tried a modified cone method in the U. S. S. R. As reported earlier in the present analysis, these attempts were entirely sporadic compared to WES's work of long standing, and involved either a number of cones or cones-cum-shear blades which measured the rotation torque, in addition to the penetration force of the instrument.

A WES equation of "mobility index" based on cone index also was quoted by Volskii with the following remark:

> "It is not likely that the utilization of this formula will lead to substantial improvement in design, and is apparently not suitable for evaluation of design different from those on the basis of which the generalizations.... were carried out."

Bevameter techniques and tests were noted without direct referencing. An agreement between experiment and predictions, using an obliquely loaded test plate, was exemplified on an unclearly described vehicle called "RAT." It appears that this case may have referred to vertically and horizontally loaded test apparatus similar to that described by Bekker (1945) and developed by Weiss (1952). Although these techniques have never been seriously considered, they may prove important if and when the problem of slip sinkage is solved (Bekker, 1969; Reece, 1965).

But this brief review by Volski of soil-vehicle interface studies does not mention Katsygin-Guskov theories of soil values, and clearly points to a still existing lag between the works of Russian automotive and agricultural engineers. The review was brief indeed; it occupied less than 3% of the complete volume. The rest pertained to hardware, which has always been of prime concern to vehicle developers.

Note that the same situation existed in this country in 1967, and still exists today. Apparently our automotive engineers do not yet recognize the necessity for acceptance of a quantitative definition of soil-vehicle interface, while American agricultural and civil engineers consider the matter essential to their own interests.

In this context it is to the enormous credit of Russian agricultural engineers that they have pioneered and tried a variety of quantitative soil-value concepts and techniques of soil measurement, although their interest was limited to the development of tractors and improvement of tillage equipment. Their efforts exceeded those of their American counterparts and of the American civil engineers, quantitatively if not qualitatively.

The efforts of Russian agricultural research has steadily gathered momentum and significance in non-agricultural off-road locomotion beyond Russia. Katsygin and Guskov (1968), in another broad sweep of the theory of tractor performance, reviewed again the Russian philosophy of soil mechanics and soil values, for the first time in the English language. Now, soil-vehicle relationship and soil values bore a meaning which went beyond agricultural applications. Familiar works of Terzaghi, Saakyan, Korchunov, Pokrovskii, and Troitskaya were reviewed again, apparently to justify the preference of hyperbolic functions over the direct exponential functions.

Once more the Bekker-Janosi equations for soil shear were discussed – and converted, so to speak, into hyperbolic functions, a feat totally admissible from the mathematical curve fitting viewpoint. It must be ventured, however, that this change of form did not change the content of the general method, although it disclosed interesting facets of the theory of land locomotion.

Only further field work and testing will show whether the Russian or American, hyperbolic or direct exponential functions of soil values, save time and increase accuracy to predictions, considering that the American soil values are general and practically

independent of the size of loading area, whereas the Russian values are not. For the time being this question will be unanswered unless, as Prof. Guskov noted, the Russian school starts changing to a more universal soil value system.

This appears to be in sight, because for Guskov, the Russian soil-values though not entirely satisfactory have shifted to another plan: they became a tool which was hopefully used in the evaluation of not only wheel or track-soil interface, but in a study of the complete terrain-vehicle systems.

In a paper on this very subject published in English, Guskov (1968) followed the system's approach as previously disclosed in Russian literature (Voprosy..., 1961; Katsygin, 1964; Guskov, 1966). His use of the Russian soil values in the evaluation of a family of tractors raises a question, however, as to the accuracy obtained because of the sensitivity of these values on the size of the loading area.

Guskov was very cautious on this subject, stating only that tests finished in 1965 "confirmed the theoretical deductions," by which he probably meant that the theory and experiment showed the same trend.

Nevertheless, he did not hesitate to outline the basic differential equations for terrain-vehicle systems analysis, which methodologically embraces all the soil values and all the vehicle parameters, susceptible to optimization by means of an approximation using Lagrange's multiplier.

If this step is correctly interpreted, the next logical step is a Russian "universal soil-value system" similar to that introduced and used in the United States for some time (Bekker, 1955; Bekker, 1963; Bekker and Butterworth, 1965; also see bibliography pertaining to the evaluation of lunar surface locomotion by NASA and aerospace industries, listed in Bekker, 1969 reference).

The need for such a system has been voiced indirectly and directly in connection with general operational studies. Parfenov (1968), of the Scientific Automotive Research Institute (NATI), gave much thought to the prevailing classification of tractors in accordance with their "nominal" drawbar pull and, upon analyzing the procedures suggested by various researchers and engineers, observed that:

"The main disadvantage of all these methods for determination of tractor pull lies in the fact that they do not pinpoint the type of soil in which the 'nominal' traction pull should be established."

This disadvantage was not newly discovered. Parfenov quoted earlier works by Hrobostov and Harhurim (1961) to show how large the differences in quantitatively unspecified soil characteristics may be, and proceeded to demonstrate the scatter of tractor pull data, on the basis of available experiments. Calling for a scientific-theoretical standardization of testing tractor-soil interface, he pointed out that his empirical curves are identical in shape to the curves computed theoretically by Janosi and Hanamoto (1961), who used $c, \varphi, k_c, k_\varphi, n, K_1, K_2$ soil-values obtained by bevameter technique.

This indirect appeal to the need for introduction of generalized soil measurement resembling those adopted by the Land Locomotion Laboratory found a strong echo in the paper by Prof. Ginsburg (1968), who worked on the very same problem of tractor classification.

To define tractor pull, Ginsburg started by quoting Bekker's (1956) definition of the DP force acting on the drawbar: $DP = H - R$ (where H is available soil thrust and R is tractor's resistance to motion) and ended by quoting the same reference as an example of theoretical determination of DP, as a function of slip. A graph of DP computed by Bekker and based on c, φ, K_1, K_2 soil-values was reproduced to demonstrate the agreement of the theory with Ginsburg's empirical data. In conclusion he urged the adoption of $DP = H - R$ definition, although he was not specific as to the type of soil values to be used.

This recognition of the American work came after a critical review by Ginsburg of traction definitions proposed by such authorities and celebrities of the Russian agricultural and automotive research as Professors B. S. Svirshchevskii (1958), E. E. Lvov (1960), D. A. Chudakov (1962), and I. I. Trepenenkov (1963).

Although no direct recommendation as to the need for a change in the Russian soil-value system was made, the implication of papers by Parfenov and Ginsburg are obvious: both were concerned with broad vehicle classification which would consider vehicle parameters besides the pertinent quantitative soil data. Since the scope of

such a classification embrases "all the tractors and all the soils" within sound engineering practice, the call for an analysis of the whole system was implicit. But the system analysis without universal soil values could not be done.

Guskov, as mentioned before, was fully aware of this deficiency in the Russian soil parametrics. And the number of those sharing his concern was growing. Nafikov and Poliakov (1968) of the V. V. Kuibyshev Military Engineering Akademy reviewed the work by Bernstein-Letoshnev (Babkov, 1959) and Bekker (1956, 1960). The latter was quoted in Russian translations published by SKB ZIL, M., (1957). In this review Bernstein-Letoshnev's soil-values k and n used in equation $p = kz^n$ were disposed of on the following grounds: the equation does not have meaning for $n \leq 0$ and/or $p < k$. Obviously, all the empirical functions used for engineering purposes have practical meaning within appropriate intervals, and not necessarily from zero to infinity. Undoubtedly the authors realized the shaky ground of such criticism, since they also repeated an old semantic argument which claims that k and n "do not have a physical meaning."

The same reasons were given by Nafikov and Poliakov for rejection of Bekker's equation $p = [(k_c/b) = k_\phi] z^n$, which brings up a question as to why by the same logic they have not rejected all the other Russian equations defining soil values. This, however, they tacitly did, because without mentioning Katsygin, Guskov, Troitskaya, etc., they proposed their own "superior" equation:

$$p = \frac{k_{NP}}{K_{NP}} \left(e^{K_{NP} z} - 1\right) \qquad (60)$$

where k_{NP} is expressed in kg/cm^3 and K_{NP} is measured in cm^{-1}.

This proposition, like another curve fitting exercise, which incidentally resembles Troitskaya's equation (21), would probably have historical value, if the authors were not interested in making equation (60) a "universal" one, i.e., in defining coefficients k_{NP} and K_{NP} independently of the size of the loading area. Although they were undoubtedly familiar with Guskov's (1966) work aimed at the same direction (see equation (26)), they preferred their own empirical formula for k_{NP} as the new universal soil value. The value was "made independent" of the test plate area A by virtue of the following empirical equation:

$$k_{NP} = k'_{NP} (1 + K_{NP}) \sqrt[3]{\frac{F}{A}} \quad (61)$$

where k'_{NP} is the soil value measured by the instrument plate having area A, and F is the area of ground contact area of the wheel or track, both in cm^2.*

On this assumption Nafikov and Poliakov deduced the vehicle's motion resistance of compaction following Bernstein-Letoshnev-Bekker method. Values k_{NP} and K_{NP} were determined experimentally by using a round penetration plate, 30 mm in diameter. However, there is no doubt that the whole concept was experimental and tentative; the authors were cautious in that respect, only stating that equation (61) "may be recommended," and nothing was given to show its reliability. But the American work performed during the past 15 years (Bekker, 1969), yields little hope in respect to better accuracy of prediction, using "generalized" soil parameters such as shown in equations (60 and 61).

It seems the whole story could have been relegated to another attempt at developing "better" soil value equations, if it were not for the Russian search for generalized soil values, needed in system evaluation, now apparently needed by the military also (Ageikin, 1970).

That search was diligently continued by Nafikov and Poliakov. In another paper by Poliakov and Nafikov (1969) – this time related to the determination of drawbar pull – they used Bekker's (1956, 1960) equation for unit soil thrust, $\tau = c + p\tan\varphi$, and described Rokas' (1960) cone penetrometer with shear blades, and the way they used it for determination of c and φ. Curiously enough they did not refer to Rokas, who used the same instrument only as an "indicator" of traction and bearing capacity for an empirical correlation with vehicle's drawbar pull.

The interpretation of soil "shear" and "vertical bearing load" data obtained by means of this instrument will be discussed in detail in the chapter on instrumentation. At

* This writer was unable to check the dimensions of this equation, because of the lack of the Russian original.

this point it may suffice to say that the concepts and methodology of deducing c and φ from a cone-cum-vanes instrument resembled those by Tsymbal (1958), Matsepura and Runtso (1961), and Rokas (1960, 1965), although no references to their work were made by Poliakov and Nafikov (1969).

However, this work may be considered as another attempt at determining c and φ, or as another exercise in a search for better soil values. Nafikov and Poliakov's activity undoubtedly represents a broader attempt aiming at a "generalized soil-values" and system analysis, since the authors state,

> "theoretical prediction of motion resistance... and traction... is irreplaceable for solution of a wide range of practical problems: design of new types of vehicles, comparative evaluation of their mobility... (and) assessment of locomotion in heavy terrain conditions... The main requirement for this type of an analysis is the determination (of vehicle performance)... by means of certain quantitative parameters of soil and of the running gear."

Obviously the solution of such a "wide range of problems" belongs to the analysis of the system.

The echo of American school of thought is heard not only in this statement; as shown before, it also reverberates in the Russian pursuit of a "universal" soil value system, and in the mathematical methodology for curve fitting, interpretation of soil parameters, and mathematical modelling of soil-vehicle interface, as will be shown in Chapters IV and V.

On the other hand empirical "indices" for predicting soil consistency show the structural complexity much more involved and more multi-valued (see Matsepuro and Runtso, 1961, and Rokas, 1960, 1965), than the structure of the simple "cone index" by the Waterways Experiment Station (WES). Details will be discussed in the next chapter.

Maintenance of agricultural machine and tractor material was the theme of a book published under the auspices of the Ministry of Agriculture of the Bielorussian Republic (BSSR), and entitled "Mekhanizatsya i Elektrifkatsya Selskogo Khozyaistva" (1968). This collective work reaffirmed the soil-values system by Guskov-Katsygin and dwelled primarily on systems planning and operations research, in conformity with the previously reported trend toward system analysis, and system economy. Similar trend also is clearly visible in the volume entitled "Trudy" (1969) and published by Tsentralnyi

Nauchno-Issledovatelskii Institut Mechanizatsii i Elektrifikatsii Sielskogo Khoziaystva Nechernozemnoi Zony, U. S. S. R. Among the many articles of this collective work, on many subjects pertaining to various agricultural problems, a short chapter by A. I. Baranskii on the evaluation of tractive indices and fuel economy of agricultural tractors, under numerous soil types and soil conditions, stresses the need for soil classification.

According to the present study, this topic was only scratched by Polish, Hungarian, and Russian students of the problem (Soltynski, 1965; Sitkei, 1967; Parfenov, 1968; Ginsburg, 1968; Poliakof and Nafikov, 1969). Thus Baranskii could not say much and had to refer to early soil classification by Baram (1963), apparently performed before 1960. Baram's classification was not related to soil measuring but to an extensive testing of wheeled and tracked tractors under the auspices of GOSNITI. From these tests empirical coefficients were deduced which enabled one to define drawbar power of tractors for the given soil class, or vice versa, and to calculate the power of intermediate soil-tractor combinations. This very crude and rather qualitative basis for soil-vehicle classification did not match the know-how of the Minsk School (Katsygin, Matsepuro, Guskov).

Although neither Guskov nor his peers contributed specifically to soil classification through measurement of the soil-values, Guskov used these values in his assessment of speed effect upon the coefficient of efficiency of a tracked tractor in the given soil. In the chapter written jointly with Melnikov on this subject, he applied his hyperbolic functions, and the generalized k'_{KA}-value, as discussed before in equation (26): ($k'_{KA} = k_S / \sqrt{F}$. The analysis aimed at establishing optima of power efficiency in terms of speed for the given soil class. The chapter describing this effort, taken up jointly with the chapter by Baranskii, the paper by Baram, and works by Guskov on soil-vehicle interface, undoubtedly illustrate a still uncoordinated, but not feeble, attempt to provide soil-values classes for quantitative system analysis. After all, even the earlier book by Guskov (1966) was entitled "Optimum Parameters of Agricultural Tractors," although he realized the lack of a universal soil-value system.

The system analysis naturally requires statistical input regarding frequency distributions of work types encountered in agriculture. Thus it seems worthwhile noting that in another chapter of "Trudy" (1969), Zhilin and Labodaev provided percentages of time

and travel length for trucks in various soil conditions (defined qualitatively). Similar statistics were given for gear changing, braking, speeds, loads, etc.

In summary, the present state of the art in Russian work on quantitative soil-values definitely points toward the consolidation of various soil parameters, which seems to lead inevitably to the evaluation of soil-vehicle system, and quantitative soil-vehicle classification for the optimization of the terrain-vehicle systems.

The influence of the American work upon this trend was not only visible but also was acknowledged by the Russian researchers in their quotations and translations. Probably, national pride and trend to originality have led the Russian effort to modify some of the foreign input, but not the methodology. The desire for intellectual independence also produced many attempts at starting from scratch, although the method has remained, in each attempt, the same as that in the American effort of the Land Locomotion Laboratory.

The Russian research work in soil value systems has proceeded on a high level of academic and engineering profession. The lead still seems to belong to the people who work in agricultural machinery. The automotive workers barely follow. The input by civil engineers appears to be non-existent.

The rather insufficient and perhaps biased referencing of Russian and foreign work, and the lack of any adherence to some agreed upon standardization of mathematical symbols and denotations, indicate an absence of overall coordination and cooperation between the various groups interested in off-road locomotion. This, however, is not a unique situation. In America, papers by the Waterways Experiment Station very seldom if ever refer to the papers by the Land Locomotion Laboratory, and vice versa. However, this hiatus exists due to the totally incompatible approaches by both American groups; in Russian, it probably exists because of bureaucracy and enormous numbers of research institutes coping with the problem. But most of their approaches are at least compatible from a methodological viewpoint.

A chronological listing of soil value definitions with the names of their originators or principal referees was shown in Table 17. The table illustrates the line of thought

of the Russian School which originated with Bernstein; it also compares that school with parallel developments in the U. S. A., England, Poland, and Hungary.

As discussed earlier, the development of soil values in these countries did encompass the U. S. A. soil-value systems, but it did not relinquish work on further search which would satisfy national and individual goals of various researchers. It also may be noted that the British and Polish works were published under the auspices of military and agricultural engineers, while the Hungarian work was published by the National Academy of Sciences, and the agricultural engineers.

Table 17

Date of Origin (approx.)	Name of the Originator (or user)	Soil-Value (Parameter) Definition	Soil Value (Parameters)	Country
1913	R. Bernstein	$p=k'(1-3^{-nz})$ $p=k_B z^{1/2}=(a'U+a''A)z^{1/2}$	k', n a', a'', or k_B; $1/2$	Germany
1936	M.N. Letoshnev	$p=k_L z^n=(a'+a''b)z^n$	a', a'', or k_L; n	U. S. S. R.
1940	I. S. Vernikov	$p=k_V z=\gamma\gamma'/[2(\gamma'-\gamma)]$	γ, γ', or k_V; $n=1$	U. S. S. R.
1947	M.N. Troitskaya	$p=p_c(e^{k_T\lambda}-1)$ $\tau=\tau_o(1-e^{-k_T\lambda})$	p_c, k_T, λ τ_o, k_T, λ	U. S. S. R.
1948	S.S. Korchunov	$p=p_{KO}(1-e^{-z/k_{KO}})$	p_{KO}, k_{KO}	U. S. S. R.
1959	S. S. Saakyan	$p=k_s\lambda^n=k_s(z/D)^n$	k_s, n	U. S. S. R.
1963	V. V. Katsygin	$p=p_{KA}\tanh[k_{KA}/p_{KA}]z$ $\tau=p\mu_m\left[1+\frac{\mu_{KA}}{\cosh\frac{x}{K_\tau}}\right]\tanh\left[\frac{s}{K_\tau}\right]$	k_{KA}, p_{KA} μ_m, μ_{KA}	U. S. S. R.
1959	Ya S. Ageikin (user)	$p=kz^n$ $\tau=c+p\mu_A$	k, n c, μ_A	U. S. S. R.
1963	V.A. Skotnikov (user)	$p=k_{SK}z$	k_{SK}, $n=1$	U. S. S. R.

Table 17 (Continued)

Date of Origin (Approx.	Name of the Originator (or user)	Soil-Value (Parameter) Definition	Soil Value (Parameters)	Country
1964-1966	V. V. Guskov, et al. (user)	$p = p_{KA} \tanh [k_{KA}/p_{KA}] z$ $\tau = c + p\tan\varphi$ $\tau = p\mu_m \left[1 + \frac{\mu_{KA}}{\cosh(\frac{s}{k_\tau})} \right] \tanh \left[\frac{s}{k_\tau}\right]$	p_{KA}, k_{KA} c, φ μ_m, μ_{KA}	U. S. S. R.
1967	S. G. Volskii (user)	$p = kz^n$ $\tau = c + p\tan\varphi$	k, n c, φ	U. S. S. R.
1968-1969	M.Z. Nafikov & I. S. Poliakov	$p = [k_{NP}/K_{NP}] [e^{K_{NP} z} - 1]$ $\tau = c + p\tan\varphi$	k_{NP}, K_{NP} c, φ	U. S. S. R.
1970	Ya S. Ageikin	$p = 1/[(1/p_s) + (\pi m_z D/2k_z z)]$	p_s, m_z, k_z	U. S. S. R.
1970	Lunar Rover "Lunokhod"	Unknown. Penetrometer, the "ninth wheel", cone-cum vanes torque-slip measurement	Unknown	U. S. S. R.
1955	M. G. Bekker	$p = [(k_c/b) + k_\varphi] z^n$ $\tau = c + p\tan\varphi$	k_c, k_φ, n c, φ	U. S. A.
1965	A. R. Reece	$p = (ck'_c + b\gamma k'_\varphi)(z/b)^n$ $\tau = c + p\tan\varphi$	ck'_c, $\gamma k'_\varphi$, n c, φ	England
1965	A. Soltynski (user)	$p = [k_c/b) + k_\varphi] z^n$ $\tau = c + p\tan\varphi$	k_c, k_φ, n c, φ	Poland
1967	G. Sitkei (user)	$p = [(k_c/b) + k_\varphi] z^n$ $\tau = c + p\tan\varphi$	k_c, k_φ, n c, φ	Hungary
1969	A. Wislicki (user)	$p = [k_c/b + k_\varphi] z^n$ $\tau = c + p\tan\varphi$	k_c, k_φ, n c, φ	Poland

CHAPTER III
ARBITRARY, EMPERICAL SOIL INDICES

Introduction

The search for generalized soil values in Russian thus far was rather unsuccessful, as could be deduced from the preceding chapter. Russian soil parameters have been strongly dependent on the size of the measuring instruments. To eliminate this deficiency, loads and loading plates of the apparatus were often developed in sizes as large as those of the tested vehicle. This was recognized as a handicap.

Since practical engineering soil problems other than locomotion, needed solutions where full size loads and loading areas were unacceptable, search for simple soil "yardsticks" continued. Thus civil engineers, who were engaged in road building and in use of construction machinery, needed a soil measure which would enable them to properly use equipment depending on the variations of terrain, climate, and geography. The agricultural engineers needed some sort of soil identification for tillage and ploughing. And those in mining were interested in soil "parameters" related to cutting and drilling.

In the same category was the question of "go - no go" of military vehicles, which was tackled at U. S. Waterways Experiment Station in Vicksburg, Miss. (WES) around 1942. The Station then introduced an arbitrarily shaped and sized cone penetrometer. The cone when forced into the ground indicated on the load scale a certain force which upon the prescribed manipulation became a measure of the "cone index" of the given soil, or of "mobility index" of the given vehicle.

By testing available vehicles in various soils (fine grained only) and checking if the vehicle could move or was immobilized in 50 passes, charts and tables of "go - no go" capability for various cone-indices and vehicles were established.

The method was publicized extensively but never widely applied by the users of off-road vehicles. The limitations of the "cone index" method in mobility studies were discussed by Bekker (1969).

Russian automotive engineers were aware of these limitations. I. V. Grinchenko et al. (1967) published a book which was reviewed in the preceding chapter, and which

stressed that the WES method will not lead to substantial improvements in design and performance.

Since the Russian users, however, occasionally expressed the need for determination, in the field, of vehicle "passability," or for some sort of soil identification for agricultural or other purposes, their interest in a quick method of prediction of soil conditions was kept alive.

Although the Russians were familiar with the WES cone penetrometer data, they could not, and/or did not, want to use them for a number of reasons, one of which was that they assumed the data was good for American soils and vehicles only. Thus they tried a number of approaches of their own, all of them different from WES.

Among others, they tried all sorts of indices of "mobility." Grinchenko et al. (1967), however, listed the names of a number of originators of such indices, and summarily dismissed the ideas by G. B. Zimelev, V. I. Knoroz, Yu E. Sharikian, Ya I. Bronshtein, G. B. Bezborodova, and V. F. Babkov. As an example, he quoted an index "proposed by various investigators (which) used the π_o factor of mobility as a parameter" in the following form:

$$\pi_o = \frac{\text{payload}}{\text{vehicle curb weight}} \text{ x average speed.}$$

The artificial structure of the resembled "mobility factors" by Waterways Experimental Station, and inevitably led to other arbitrary indices of limited usefulness and applicability, as reviewed below.

Rokas Locomotion Indices (SSG-3)

Apparently because of their critical attitude to the "WES cone," Grinchenko and his colleagues did not elaborate at all on the Russian cone by Rokas (1960), although they discussed rather extensively flat plate penetrometers, soil penetration curves, and their interpretation by means of the Bernstein-Letoshnev formula $p = kz^n$ for various values of n.

As could have been expected, a definition of an arbitrary index of mobility was not favored in the automotive handbook for cross-country vehicles, published in 1967,

however, a civil engineering magazine published an article on this subject by S. I. Rokas, in 1960.

Rokas was dissatisfied with the simple cone penetrometer as a tool for determination of the drawbar pull, motion resistance, and traction. He sought for an index defined in terms of values more meaningful than the "cone index." Hence he addressed himself first to the general question as to how to estimate performance in changing soil conditions due to climate and geography, and started with work by Babkov (1956) who defined mobility of "go" by the drawbar pull DP in the following form:*

$$\frac{DP}{W} \geq \frac{H - R}{W} - f \geq \tan \beta \qquad (62)$$

where H is the required soil thrust; R is motion resistance of the soil working machine; f is the unit rolling resistance of the tractor; W is tractor weight; and β is the angle of terrain slope. For transportation only:

$$\frac{DP}{W} = \zeta \mu_a - f_{sr} \geq \tan \beta \qquad (63)$$

where ζ is the coefficient which defines the magnitude of load on the driving axle or running gear, and μ_a is coefficient of "adhesion" between the vehicle and the ground.

Rokas was not entirely satisfied with the form of these relationships because it did not reflect directly the changes in DP/W due to soil variation. In all probability he was not yet familiar with bevameter values which encompass pertinent factors. Thus, to include soil variations he assumed undefined functions Ψ_1, Ψ_2 which express "passability" Π and coefficients μ_a and f in a general manner:

$$\left.\begin{aligned} \mu_a &= \Psi_1(\tau) \\ f &= \Psi_2(p) \\ \Pi &= \Psi_1(\tau) - \Psi_2(p) \end{aligned}\right\} \qquad (64)$$

where τ and p defined shearing and bearing strength of the ground, respectively; Π was index of "mobility."

* This is identical to Bekker's (1950, 1956) definition.

To quickly determine for the given vehicle "soil indices" $\Psi_1(\tau)$ and $\Psi_2(p)$, Rokas constructed at the Moscow Highway Institute (MADI) a special instrument called "SSG-3," which consisted of a cone penetrometer equipped with shear vanes. The cone served to determine p functions, and the vanes, τ functions. The method of instrument's use and its construction will be described in the next chapter. At this time it may be suffice to note that the method consisted of recording $\Psi_1(\tau)$ and $\Psi_2(p)$, and of empirically correlating Π, μ_a, and f (equation 64) with τ and p for each specific vehicle, in terms of "go - no go" (equations (62), (63)). In this respect only, the method was a duplication of the "cone index" procedure developed by WES. The Russian procedure and the instrumentation, however, were more sophisticated than the WES "cone penetrometer," inasmuch as the "SSG-3" instrument indicated both the vertical load $\Psi_1(p)$ and the shear load $\Psi_2(\tau)$ produced by the cone and the vanes.

This method was recommended by Rokas to the user for selecting the right vehicle for the given soil conditions. The selection was based on the previous testing of each considered vehicle under given soil conditions for τ, p, μ_a, and f. The method, however, could not help designing better new vehicles; this was the apparent reason why Grinchenko et al. (1967) did not consider it, beyond mentioning its existence.

Rokas stressed the simplicity of his instrument and of its operation, but did not originally reproduce functions Ψ_1 and Ψ_2 with reference to any vehicle.

His ideas were further elaborated in 1963 in an automotive magazine, where some correlations with motion resistance were reported for a ZIL-157 truck at various soils and inflation pressures (see the next chapter).

This work was, as far as it could be ascertained, the first attempt to produce for the automotive user, some arbitrary soil values and an empirical correlation with performance indices of available vehicles which had been tested previously under soil conditions $\Psi_1(\tau)$ and $\Psi_2(p)$. Grinchenko et al. (1967) thought that Rokas' method was superior to the Waterways Experiment Station method, although they dismissed it rather tersely.

The present writer did not find in the leading automotive and agricultural literature more information on the use of cone-cum-vane penetrometer and of the arbitrary soil indices $\Psi_1(\tau)$ and $\Psi_2(1)$.

This did not mean that the work on Rokas' idea had stopped. It probably implied that the application of the idea ran into trouble; for about 1969, another, modified approach was made in this area with an unmistakable effort at rationalizing the method. Curiously enough Rokas was not mentioned at all.

Poliakov-Nafikov Locomotion Indices

Poliakov and Nafikov (1969) started with a general premise for a need of simple soil measurements in the field, in order to enable the user to predict the coefficient of vehicle adhesion μ_a and motion resistance f. Without any preliminaries they accepted a very simple, small soil testing apparatus, the cone penetrometer with vanes, and with the Rokas Ψ_1 and Ψ_2 indices. Since no reference to Rokas' work was made, the identification of the equations and even the correction of some of the apparent errors was complicated. What was new here was the assumption based on Bekker (1956), and Ageikin (1960) that coefficient of "adhesion" μ_a is:

$$\mu_a = \frac{c}{p} + \tan\varphi = \frac{\Psi_1(\tau)}{\Psi_2(p)} + \tan\varphi \tag{65}$$

The fallacy in using the cone-cum-vanes penetrometer for a performance model such as expressed by equation (65) laid in the fact that the determination of c and φ by this technique was subject to the crudest approximation. The error was caused by the dissimilarity of load and deformation areas of the instrument and the vehicle; it also was caused by applying the arbitrary rule according to which Ψ_1 and Ψ_2 were taken as mean values of two penetration tests of an arbitrarily shaped and dimensioned instrument (see next chapter).

Motion resistance f was determined by using the cone as a penetrometer. To justify this the authors referred to their earlier work (Nafikov and Poliakov, 1968) although it stated that in order to obtain a representative load-sinkage curve, "one must use a penetrometer, with the contact area equal to the contact area of the tire." Since this they found "very inconvenient," they "verified experimentally that for this purpose a penetrometer of small area also may be used. But most convenient was a rigid disc, 3 cm in diameter...." How this reasoning later led to the use of the cone was not explained.

In any case, they applied Bernstein-Letoshnov-Bekker equation for motion resistance:

$$R = \int_0^z p\,dz$$

in order to determine $f = R/W$. To accomplish such a task, when using cone-cum-vanes device, without considering the differences between cone and round plate raises serious doubts as to the rationale of this attempt.

Obviously Poliakov and Nafikov encountered great difficulties; thus in the next publication (Poliakov and Nafikov, 1969 a) they talked about purely empirical correlation between vehicle passability and the "indices" Ψ_1 and Ψ_2 measured by the cone-cum-vanes penetrometer, apparently dismissing equation (65).

Again Rokas was not mentioned. Surprisingly his penetrometer was now described as either a hand operated instrument weighing 3 to 5 kg, or as a mechanically operated instrument weighing 300 to 500 kg. Evidently the "indices" did vary within a wide range, depending on the size of the instrument. Apparently functions Ψ_1 and Ψ_2 had to be empirically correlated with vehicle "go - no go" performance, not only considering the soil but also the instrument and its size.

Why Rokas was totally ignored by Nafikov and Poliakov remains a mystery. But perhaps the answer to this question is irrelevant. However, from the historical viewpoint which elucidates the cultural and the social, it may be pertinent to note that the proponents of the cone-cum-vanes "indices" for locomotion purposes came from the civil engineering school of thought, in a perfect analogy to the American advocates of the "cone-index" and the British "shear-vane index," both of which also stemmed from the same school.

"Universal" Multi-Purpose Indices

Rokas-Poliakov-Nafikov cone penetrometer with shear vanes was an obvious marriage of the WES cone (Knight, 1956) and the British shear vane (ORG, 1947). This author believes it has been a unique combination of its type, although later Cohron (1963) tried unsuccessfully to achieve similar goals, using a round penetration plate with shear vanes. All the other instruments embodied separate definitions of indices, either in penetration or in shear, using separate devices.

As far as could be ascertained the first plate-penetrometer used for agriculture purposes was devised by R. Mayer, around 1910 (?), and introduced by Bernstein (1913). This led to the "indices" of "soil strength" as shown in equation (6). Curiously, Mayer-Bernstein indices k, n were taken with plates 2, 2-1/2, 3, and 4 cm diameter, i. e., close to that reluctantly recommended by Poliakov and Nafikov (1969), 53 years later. Similar attempts were observed in the United States. McKibben (1940) dwelled on an arbitrary "index" of flat plate penetration, which he tried to correlate with wheel performance. To this end he borrowed the idea of the "Proctor needle" (Proctor, 1933), which was identical with the Mayer (1910) penetrometer. Letoshnev, obviously familiar with these works, followed suit, but his "indices" did not provide a basis for arbitrary empirical correlations with wheel performance. As shown in Chapter 1 the still unresolved effect of penetrometer size was considered in a rather complex and indecisive manner.

Although Letoshnev's concern with theoretical correlation of soil parameters and vehicle performance was shared by all the Russian students of locomotion, the much more complex problems of soil polughing and tillage defied for a long time any rigirous solutions. Thus the work on empirical arbitrary soil indices which would do everything at practically no cost, continued.

If the present author is correct, the omnibus requirement for a universal solution was formalized in February 1946 at a conference held by Soil Institutes of the Academy of Science U. S. S. R. (Amplevskaya, 1955). One of the resolutions urged that:

> "for solving the problems of the load of agricultural tractors, establishing work standards for tillage and planning fuel economy, it is necessary to know specific soil resistance during plowing. Inasmuch as the determination of such resistance is very tedious by dynamometric methods, it is recommended that investigation be undertaken in order to define specific soil resistance by means of physico-mechanical soil properties. "

The language of this resolution was not quite identical with the wording of an earlier resolution by the British, Canadian, and American committees concerned with vehicle mobility in "adverse soil conditions":

> "... now that time is available we urgently invite consideration of a long range research program... to develop basis on the relationship between soils and vehicles... to refute, modify, or confirm existing theories on... vehicle mobility and soil physical characteristics. " (SAE, 1945).

The Russian resolution led to a lengthy and expensive search (Soil Institute of the Academy of Sciences and the affiliated institutes) for a "specific" soil parameter which could be measured easily in the field, and converted into plough, tiller, or vehicle performance parameter by means of simple manipulation.

The U. S. effort, however, was two-pronged: The Land Locomotion Laboratory followed the Society of Automotive Engineers' resolution looking for a scientific definition of soil-vehicle interface, while the Waterways Experiment Station concentrated on single empirical "soil parameter," which would answer all the questions in one index.

The extent of the Russian effort was enormous (Amplevskaya, 1955). It was based on empirics, gradually switching to theoretical mechanics. Originally, it included studies aiming at establishing relationship between soil structure, strength, and chemistry (Oganesyan, 1949). It was thought then that soil resistance to ploughing and wheel rolling could be found in some relationship to a simple penetration test, where load p_p acting on the penetrating tip of the instrument (all shapes of the tip were tried) could be correlated with plough resistance f_p measured in load units per unit of plough area, projected in the direction of motion:

$$\nu = \frac{p_p}{f_p} \tag{66}$$

On that basis a series of empirical equations was proposed, which were not satisfactory. As a result Amplevskaya (1955) proposed a small scale-model blade and empirically determined the relationship between model drag f_m and plough drag f_p (kg/cm^2) for various soils. Obviously, f_m was a much better "index" of plough draft than the "penetration index" p_p. Curiously enough, no dimensional analysis was reported by Amplevskaya, and the difficulties with the introduction of Coulomb's equation, hence soil values c and φ were claimed.

This approach apparently reflected a general trend in which simple "indices" were expected to make predictions of complex phenomena – the philosophy that wasted enormous amounts of time and effort both in Russia and America.

However, the highway engineers were more incisive and rigorous in this game than their agricultural colleagues. Palovnev (1960) developed a method of bulldozer performance prediction, using the following soil "indices:" cohesion c, internal friction φ,

coefficient of friction soil-metal μ, and density γ. Reference to the classic work by Sokolovski (1954) was made, though a comparison with another classic by Söhne (1956) was lacking. A more rational approach to soil cutting also was made by Sineokov (1965) who quoted exhaustive literature and used soil values c and φ as soil "indices."

Attempts to relate cutting resistance of soil to the tool by means of some sort of a single "index" were made repeatedly. Vetrov (1957) reported impact penetrometer tests and concluded that the "index" construed as a number of blows needed to force a circular plate to the depth of 10 cm cannot be correlated with draft in soil cutting. He probably knew that similar technique was used in Switzerland, in avalanche prediction. But his study was a rather hopeless move toward a simplification of complex soil behavior. The Swiss impact penetrometer (Haefeli et al., 1939) was never applied to snow properties identification; it only served the purpose of detecting snow stratification.

Obviously the problem of soil identification by means of a primitive empirical index for the multiple and complex purposes was not soluble. Nevertheless almost everybody tried some simple solution, with the exception of the Land Locomotion Laboratory in Detroit. Even the scholarly work, and a classic in itself, written by Zelenin (1950) under the seal of the U. S. S. R. Akademy of Sciences, Institute of Mines, did not refrain from speculating on the empirical relationship between soil cutting and soil penetration by an impact penetrometer (DORNI I) and impact "index."

Other "indices" obtained with penetration of wooden cones served the purpose of defining "hardness" of snow cover or correlating wheel sinkage in snow with the "index" (Kragelski, 1945). In the same vein, Zaleski (1956) advocated indices of "hardness" or "soil compaction" introduced by Revyakhin and Goryachkin. However, Zaelski detected much arbitrariness in the interpretation of the "indices" and proposed a method as to how to read load-penetration curves; to this end he tried all kinds of penetration tips. The best example of confusion was the author's statement:

> "it is considered that the penetrometer with a flat point has the action that most closely approximates the action of tillage tools and agricultural machines."

To standardize the "indices" thus obtained, the All Union Institute of Mechanization of Agriculture in Leningrad tried to freeze the method of penetrometer readings (see the next chapter).

Tsymbal (1958) attempted to do better. He decided that his cone penetrometer should measure, in addition to "soil hardness," coefficients of friction of soil-to-soil and soil-to-metal in order to identify "soil as an engineering material," in agriculture. Katsygin and Aziamova (1960) devoted the whole chapter in the respectable series of "Voprosy...," to the problem of defining physico-mechanical properties of agricultural soils by means of "indices." Here, the bearing capacity of soil was defined in terms of a load-penetration curve of a "standard" penetrometer equipped with four different sized round plates. This apparently did not suffice, for complex "indices" obtained with three arbitrarily shaped cones also were discussed (also see Matsepura and Runtso (1961). As if Atteberg's indices were not sufficient, another "index" attributed to P. O. Boychenko was described as an improvement.

However, penetration tests could hardly be correlated with plough draft and tractor pull. Therefore Kuznetzov (1962) further tried a shear test similar to that by Bevameter, but called it a "hardness" test performed by rotational "durometer." Arbitrariness of his indices was not mitigated by tying them to Goriachkin's equation for the effect of shear speed. The empirical and misguided character of this work was illustrated by an attempt to link the results obtained by the "rotational durometer" and the penetrational test of the Revyakin penetrometer equipped with a 1 cm^2 disc tip.

Note that Sitkei (1967), in Hungary, preferred to follow standard theories of soil shear and penetration as expounded by Katsygin and Guskov (1968), Bekker (1956), and Sohne's (1956), rather than the arbitrary empirical indices. In this respect he was closer to the U. S. and the German than to the Russian School. The Polish school, however, showed, at that time, a mixture of theory and empirics (Bernacki, 1960): besides attempts of mathematical analysis of soil-tool interface, arbitrary "compactness" indices obtained with at least 5 different forms of penetration plates were accounted for.

This was further followed by Russian empiricists. Vysotskii (1965) devoted much thought to "new" integrating instruments for determination of physico-mechanical indices of soil. But the novelty of the index integration consisted of mechanical averaging of fluctuating load-penetration values and of variations of frictional forces produced by traditional penetrometers. The arbitrariness of "indices" thus arrived at remained the same. Nevertheless the author recommended that the "indices" may

be used not only for the correlation of performance of agricultural machinery and soil, but also for correlation of other "agricultural" materials and fertilizers. Such an amplitude of applications casts serious doubt as to the soundness of this line of thinking.

The Future of "Indices"

To sum up, the arbitrary soil "indices" were originated primarily by the Russian agricultural engineers who tried to solve more problems than locomotion alone. While the Russians later dropped the empirical indexing whenever vehicle performance and design were concerned, the American "cone-index" data are still advocated, even for design purposes.

All these indices have played a negligible role in modern locomotion development. Neither the user nor the designer could have applied them to their purposes. For the "indices," as the Russians and the Americans found, cannot be used in system analysis, since they lack physical dimensions translatable into terms of soil-vehicle interface. And the philosophy of their interpretation, based on the hopes of solving the multi-variant complexity with a uni-value simplicity, has never met expectations.

The present review of the Russian search for arbitrary locomotion and multi-purpose indices shows how unplanned, haphazard this activity was. In essence, it was a scramble for amateurish ideas which would hopefully do very much for very little. The ideas were repetitious and unimaginative until the advent of Katsygin-Guskov soil values, which conceptually and methodologically are identical with bevameter approach.

There seems to be little doubt that in the seventies, arbitrary indices produced by simple "penetrometers," durometers," and "strengthmeters" of soil will find little if any application, either in locomotion or in agriculture.

This conclusion is further strengthened by the review of instrumentation developed during the past half century, as shown in the next chapter.

CHAPTER IV
INSTRUMENTATION FOR SOIL MEASUREMENTS

Introduction

Soil values and arbitrary soil indices developed in Russia between the early twenties and the sixties, as described in the two preceding chapters, show to what extent an analytical and more rigorous approach to soil properties was diffused with a haphazard search for arbitrary empirics.

This activity naturally was followed by the development of measuring devices and instrumentation. Their chronological review throws much light upon the molding of the school of thought from primitive concepts to modern solutions, and appears to be most educational to the student of locomotion.

The description of the Russian instrumentation referred to in this chapter was not easy because of the frequent availability of poor drawings and photographs or of sketchy explanations. Sometimes, drawings were not available, and instrument designation was quoted without any specifications. This required some search in depth in order to identify the equipment.

Another problem arose with the timing of the appearance of the given instrument. The dates quoted refer to the date of the publication in which the description of the instrument appeared. Whether it was the first appearance or not was judged from the form of the description and from the references quoted. Obviously, the apparatuses had been under development and testing for sometime prior to the publication. But the establishing of this type of "birth date" was almost prohibitive.

The writer hopes that in spite of these shortcomings the story was told without serious omissions or mistakes, and with a sufficient clarity in order to draw pertinent conclusions.

Mayer-Bernstein Penetrometer (1910 - 1913)

The arch prototype of soil penetrometers, for locomotion purposes, is Mayer's (1910 ?) instrument reported by Bernstein (1913). As far as could be ascertained, a similar

American device dates back to Proctor (1933), who used it for civil engineering purposes. Since this kind of a penetrometer was the basis for the Russian penetrometer, starting on a firm basis with Letoshnev (1936), a brief review of the device is in order.

Figure 1 shows the general view. Penetrometer plate 1 was fastened to rod 2, and was actuated by handle 3 through spring 4. The load was recorded on paper drum 5 by means of a pen actuated horizontally by string 6, which moved with the deflection of spring 4. The vertical movement of the pen was controlled by rider 7, which moved downward with penetrating plate 1. Legs 8 provided sinkage reference and stability for the device. The vertical movement of the recorder was effected by means of a rather complex, balanced parallelogram, which though briefly described was not clearly discernible on the drawing. The adjustment of the "zero point" was performed by means of special screws.

In addition to the instrument, Figure 1, Mayer tried another load-sinkage apparatus in which the spring was replaced with weights.

The penetrometer plates originally used were 3 cm in diameter; they were found later to be too large for hand measurements of the stubble. The dependence of the load-penetration curve on plate size was fully understood. Tests with diameters, 2, 2-1/2, 3, and 4 cm were performed, and successfully correlated with wheels of the same width. This was the beginning of Bernstein-Letoshnev's soil values as described in Chapter II.

One must marvel at the precision and faultless premises of Bernstein's work. His goals were rather limited, but the achievements were full of long lasting success.

Bernsteinian soil value k_B was obtained by "hand fitting" the $p = k_B \sqrt{Z}$ equation into the measured curve. Apparently Bernstein did not make experiment. with single wheels; in order to verify his equations for rolling resistance of rigid wheels he used data obtained by Morin (1840 to 1841) for four-wheel carraiges. To this end he modified his single-wheel equation into a two-tandem-wheel formula (for details see Bernstein, 1913). This approach was followed by Letoshnev (1936), as he too was ultimately interested in four-wheel carriages and not in the single wheel.

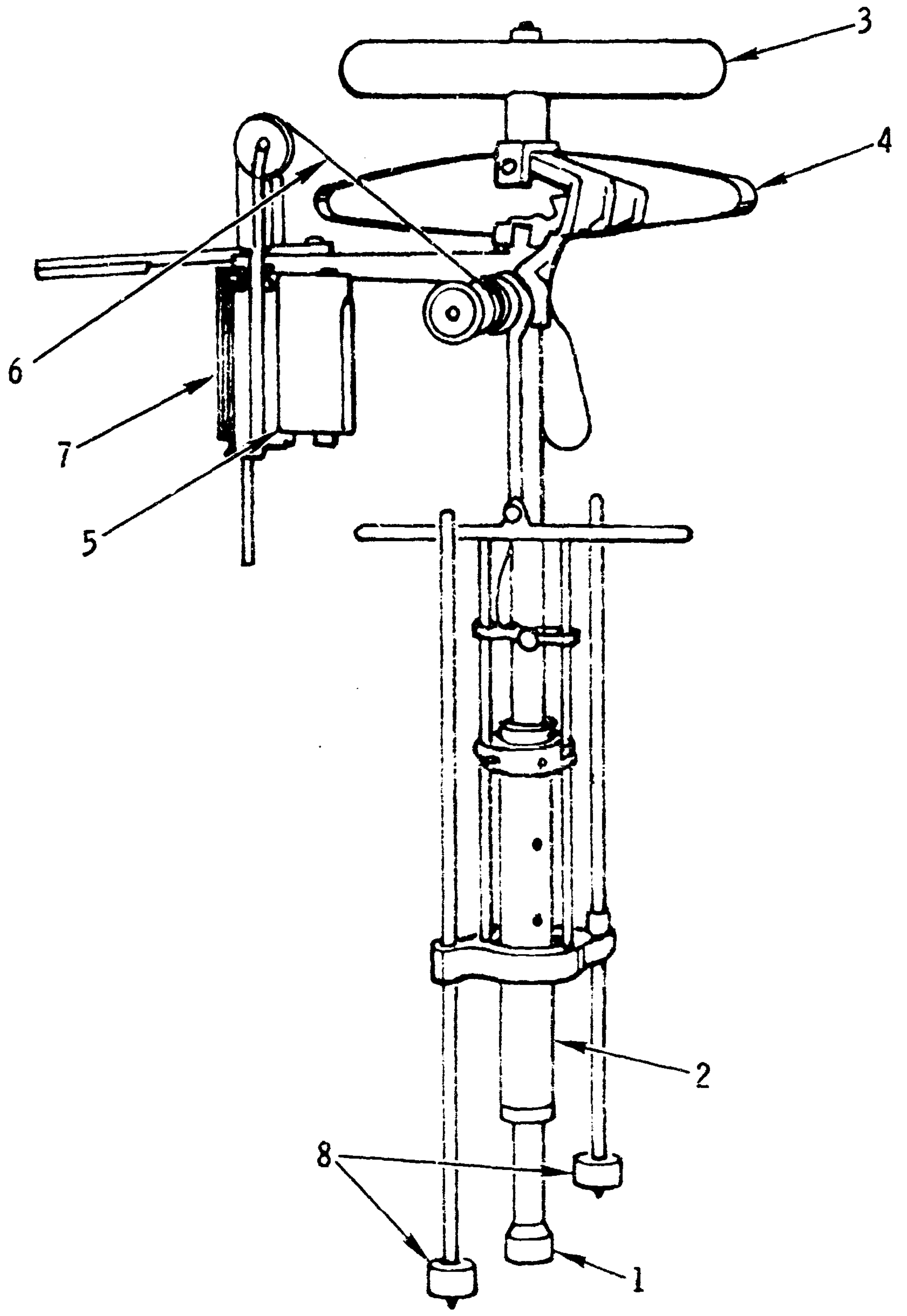

Figure 1 Mayer (1910?) Soil Penetrometer for Locomotion Studies (after Bernstein, 1913)

This logical trend is in sharp contrast with American work in which up to this time more than 95% of the research had been devoted to single wheels, with an almost complete neglect of multi-wheel carriages (Bekker, 1969) and corresponding soil penetration tests. The paradoxical situation and intolerable bottlenecks that arose because of this lack of purposiveness in research on land locomotion mechanics has been illustrated in the reference by Bekker (1969 a), which also reviews all the available modern instrumentation that may be derived from Meyer-Bernstein penetrometer.

Letoshnev's Instrumentation (1936)

Instrumentation used for soil measurements in Letoshnev's expansion of Bernstein's theory was not explicitly described, at least in the excerpts of his work available to this writer. There is no doubt, however, that he was totally familiar with Mayer's penetrometer, as well as with the prolific works of the venerable academician V. P. Goriachkin, who between 1906 and 1924 covered practically all aspects of agriculture, including "physico-mechanical and agricultural properties of soils," and was acclaimed a Father of Russian agricultural research (Dubrovski, 1955; Trak i Sielhozmash, 1969). Goriachkin developed a penetrometer which was widely used with the so-called Revyakin's penetrometer for measuring soil compaction (Zaleski, 1956). Detailed specification of these two penetrometers is, at present, lacking. This gap, however, in the analysis of Letoshnev's work does not appear to be critical because, as mentioned before, he was concerned with four-wheel carriages and used to determine soil value k'_B for $n = 0.5$ for various soils from equation 13 quoted in Chapter II. Thus, knowing wheel diameters D_1 D_2, load W, load distribution coefficient upon front and rear z, and the draft R, Letoshnev's k'_B for the complete carriage was determined from equation

$$k'_B = \frac{4W^3}{9(\zeta + 1)^3 R^2 b} \left[\frac{2\zeta}{\pi\sqrt{D_1}} + \sqrt{\frac{1}{D_2} + \frac{4\zeta^2}{\pi D_1}} \right]^3 \ldots \qquad (67)$$

for $n = 0.5$. For soils having $0 \leq n \leq 1.5$ the solution becomes more complex (Bekker 1956).

In brief, Letoshnev's instrument was based on the wheel carriage under investigation. By varying load, design parameters, and the soils within realistic limits he could tabulate soil properties k'_B for locomotion prediction. These properties as shown in

Chapter II were reducible to those measured with comparable penetrometer plates. Since Letoshnev's objective was to classify loads per horse for a number of typical carriages and typical agricultural soils, he achieved his goal without the need for a generalized instrumentation.

Snow Penetrometers IMASh and NIAS (1945)

Snow problems originally investigated in Russia had only indirect connection with locomotion. Extensive studies sponsored by the Russian Academy of Sciences were more concerned with snow as a structural material for aircraft landing strips, and with snow removal and compaction rather than with over-snow transport.*

Abroad, the situation was the same: each country had its special interest, and the early Swiss research, for example, concentrated on avalanche prevention (Bucher, 1948), while the Swedes worked on sled transport (Eriksson, 1949), and the Japanese on snow physics (Nakaya et al., 1934 to 1936). Accordingly, the Russian work on snow measurements was considered by many as unique. The review of instrumentation used for that purpose, however, seems to belittle this conclusion.

First, Russian scientists adopted the old Grandvoinet equation for motion resistance of a rigid wheel in order to evaluate resistance of snow compacting roller. As shown in reference (Bekker, 1956), Gradvoinet's equation is identical with Goriachkin's and both are equivalent to Bernstein-Letoshnev's formula for $n = 1$:

$$R = \alpha \sqrt[3]{\frac{W^4}{r^2 b\, k_L}} \tag{68}$$

where r is the radius of the roller. As this equation was based on $p = k_L z^{n=1}$, it was totally unacceptable because not only k_L but also n-value varied with snow density and stratification. Thus, in the final analysis Kragelski (1945) resorted to an artificial substitute for k_L, measured as a snow "hardness" for various snow states, with a round plate of fixed area 6 cm^2. The "hardness" was then experimentally correlated with R. At another stage, snow "hardness" was reported by Kragelski to have been measured with a ball 3.3 cm^2 in cross section.

* The early development of propeller driven sleds did not entail snow research (Juvenatiev, 1939).

In general, according to Kragelski (1945) "hardness was measured by means of a penetrometer equipped with a special tip, sphere, cone, pyramid ... (though) at present plungers having plane contact surface (are used)." The hardness was defined as the pressure at 3 cm sinkage. The chaos which resulted in this kind of snow hardness definition led to another misconception based on attempts of selecting such a shape of the penetrating body that the unit load would remain constant, irrespective of penetration. This came from the recollection of 1888 by Karpel, and the 1907 work by Ludwig who found that in testing metals (sic!) one must use "a cone or a pyramid" in order to obtain a fixed index of hardness (Kragelski, 1945). Additional references to Vickers' hardness index illustrated the untenable premises of this school of thought. Nevertheless, a specific cone penetrometer was adopted, and the snow "hardness" was defined as a measure of load divided by the base area of the cone at given penetration.* The Institute of Mechanical Engineering of the U. S. S. R. Academy of Sciences developed for that purpose the instrument shown in Figure 2 (Kragelski, 1945).

The penetrometer, with a wooden cone designated IMASH, was operated manually by pressing handles 1; this compressed spring 2, the deflection of which (load) was recorded on dial 3. The cone was marked with circular lines at 10mm intervals, enabling one to use it at partial penetration, when measuring hard snow, and to determine the corresponding cone base area for the calculation of the index. The instrument was allegedly dropped after two years of use. At the same time, Kharkov and Kragelski (Kragelski, 1945) conceived a simpler and more reliable device (so they claimed), as shown in Figure 3. It consisted of cone 1 and loading platform 2 attached to frame 3. The cone was made of wood covered with metal. It had an angle of 45°, but the same height (130mm) as the cone used with instrument in Figure 2.

Base plate 4 provided support for the instrument on snow surface, and reference point for the penetration scale. Pointer 5 attached to the moving structure of the cone and the load plate indicated sinkage.

The scale also had red marks which denoted specific cone penetration corresponding to the size and load of aircraft tires that would sink to a depth of 3 cm.

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* This was practically identical to the WES "cone index" definition adopted at the same time, for soil.

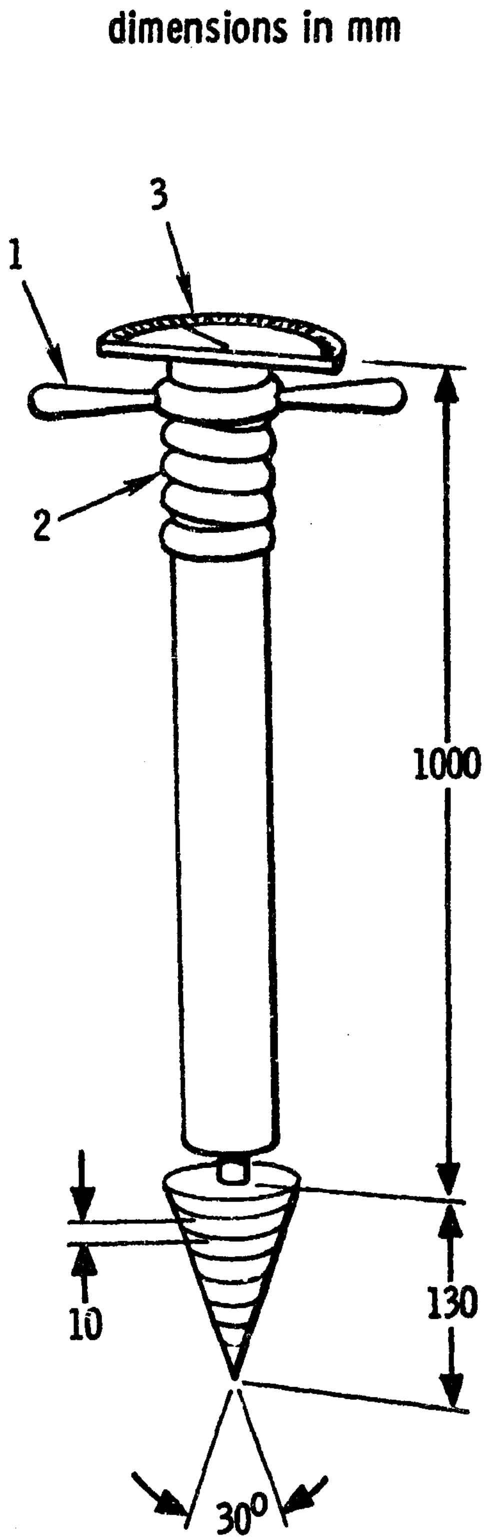

Figure 2 Snow Penetrometer of the Inst. for Machine Design, U.S.S.R. Acad. of Science with IMASH cone (Kragelski, 1945)

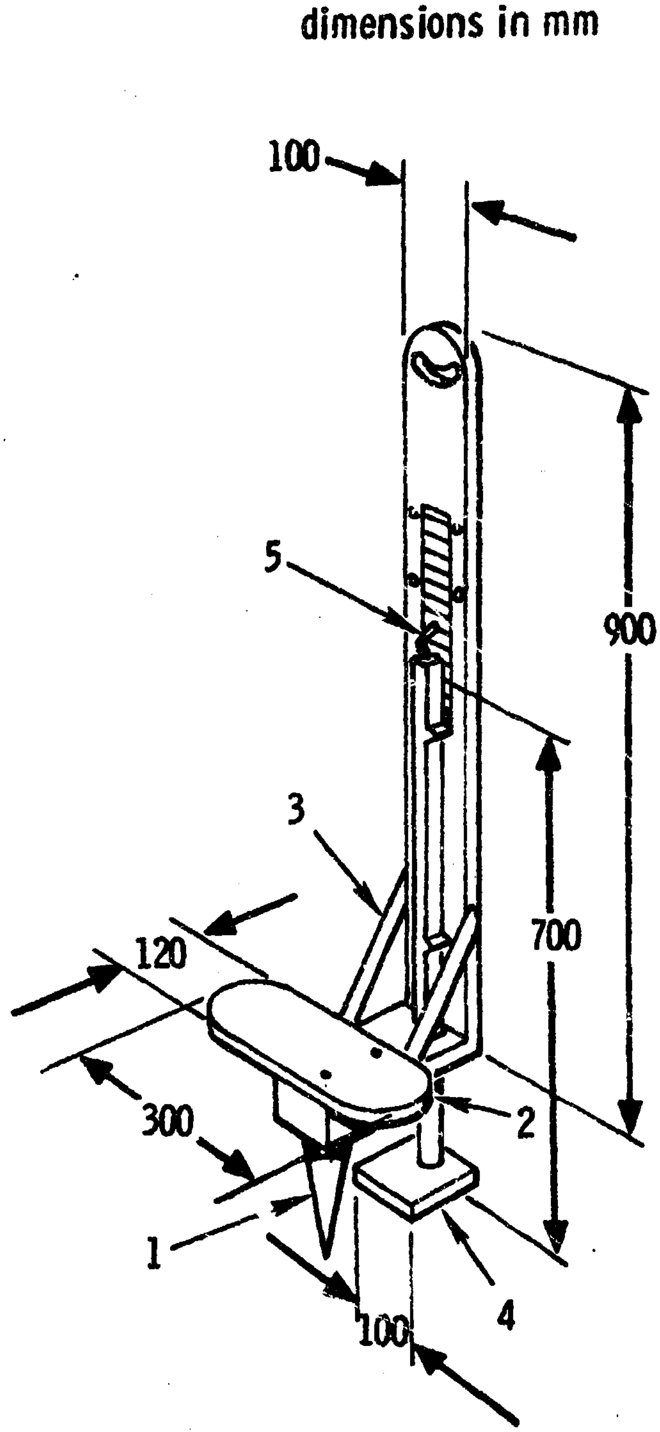

Figure 3 Snow Penetrometer of NIAS Type (Kragelski 1945)

The instrument was developed for testing snow-covered runways. It required 15 to 20 measurements in order to obtain an acceptable correlation between "cone index" and aircraft "landing - no landing" index defined by sinkage. It apparently worked in compacted uniform snow.

The specialized application of the instrument, and the lack of theoretical foundation for the simplest generalization of the measured values, were undoubtedly responsible for its limited use. No application to over snow or soil locomotion was recorded by this writer.

Soil Penetrometers DORNII and VIME (1950)

Extensive work by Zelenin (1950) devoted to soil cutting described an impact penetrometer, DORNII, as an instrument for measuring "soil hardness, particularly (useful) for road construction." He also mentioned a "static" device called VIME, which according to a one-sentence description seems to have resembled, in concept, the penetrometer in Figure 1.

DORNII penetrometer, Figure 4, was like the Swiss "Ramsonde" or an earlier vintage (Haefeli, 1944). Weight 1 (2.5 kg) could be lifted 0.4 m above base ring 2 and dropped, thus forcing plate 3 into the ground.

The number of strokes needed to force the plate into the ground by 10 cm was a measure of hardness. Penetration plate 3 had an area of 1 cm^2. The device could be operated "upside down," with the other end having penetration plate 4 with cm^2 area.

The problem, of course, was to correlate the arbitrary impact "index" with soil resistance in cutting. An enormous amount of work went into this undertaking, with totally questionable results as reported by Vetrov (1957). No application of DORNII to locomotion was noted by this author in the Russian literature, or elsewhere.

Soil Measuring Instruments in Other Countries (1930 to 1950)

To fully appreciate early development of Russian soil measuring instrumentation and its primitive and unimaginative nature, note that the same situation prevailed in other countries preoccupied with the development of "ad hoc" devices expected to resolve inaccessible complexities with disarming simplicity.

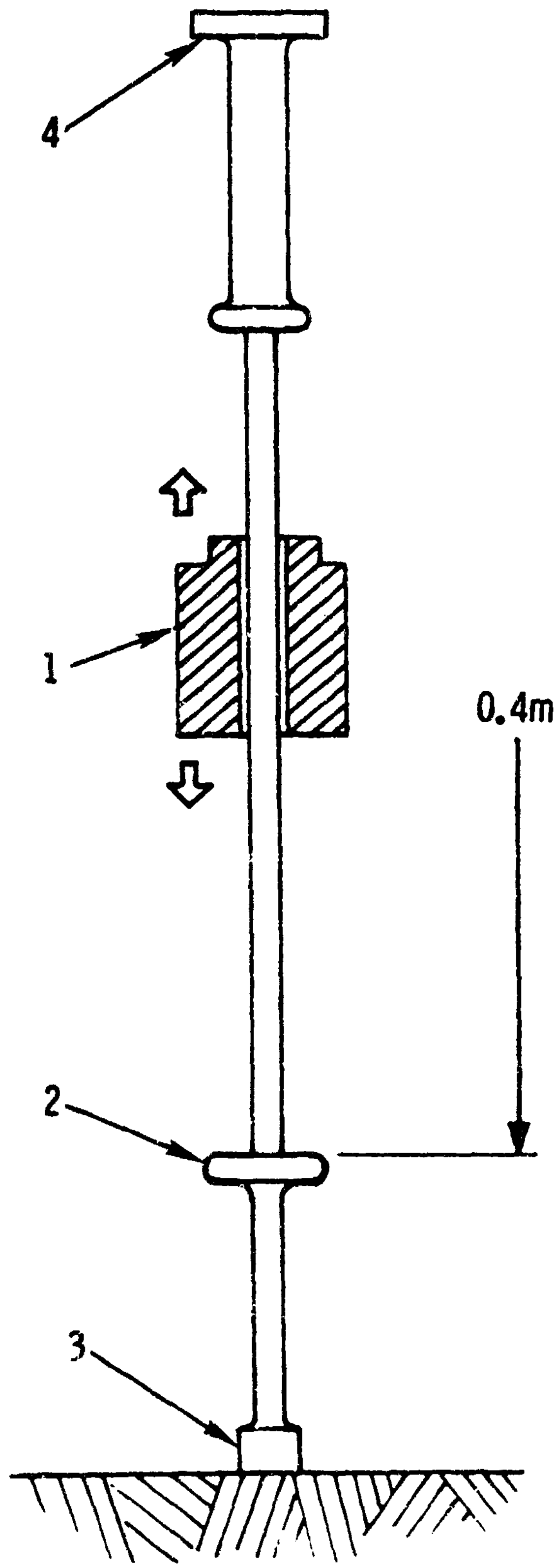

Figure 4 Impact Soil Penetrometer, type DORNII (Zelenin, 1950).

Hence, in America, civil engineer Proctor (1938) introduced his "needle," which was identical with the Russian "static" DORNII mentioned by Zelemin (1950). In the early forties the Waterways Experiment Station introduced the "WES cone penetrometer," which in principle looked like the Russian snow testing device, Figure 2 (Kragelski, 1945).

The founder of American agricultural locomotion research, McKibben (1940), was apparently so overwhelmed with the multiplicity of gadgets available for his wheel research, that he tried a number of impact and static penetrometers, Figure 5. For the purpose of soil description, he used standard civil engineering qualitative notions of liquid and plastic limits, as well as plasticity index.

In science, the cultural heritage builds progress, maintaining some degree of predictable continuity. Work by Ohm and Faraday, Pasteur and Einstein live in abstract symbols, intellectual tools and procedures often called by their names. Thus the future course of evolution continues, without starting from scratch. Not so in off-road locomotion. Here no one knows what was what, and why.

Thus McKibben called the "Swiss Ramsonde" and the Russian DORNII penetrometer, the "Iowa penetrometer" (Figure 5a); a simple plunger with sinkage indicator (Figure 5b) was named the "Rototiller penetrometer;" and the original device conceived by Mayer-Bernstein was called the "Proctor plasticity needle" (Figure 5c).

As could be expected, McKibben and his co-workers attempted the correlation of the "indices" by these gadgets with wheel performance, probably without knowing much about Mayer, Bernstein, Kragelski, Vetrov, etc.

The British acted in a similar, though more rational, manner. They seriously worked with Mayer-type penetrometer (without naming it), although it seems they were not familiar at that time with Bernstein-Letoshnev's theories (ORG, 1947). Since they wanted more precision they developed a self-recording constant-rate penetrometer* in order to follow their own theory of load-deformation (Figure 6).

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* Vehicles sink at constant load rather than rate.

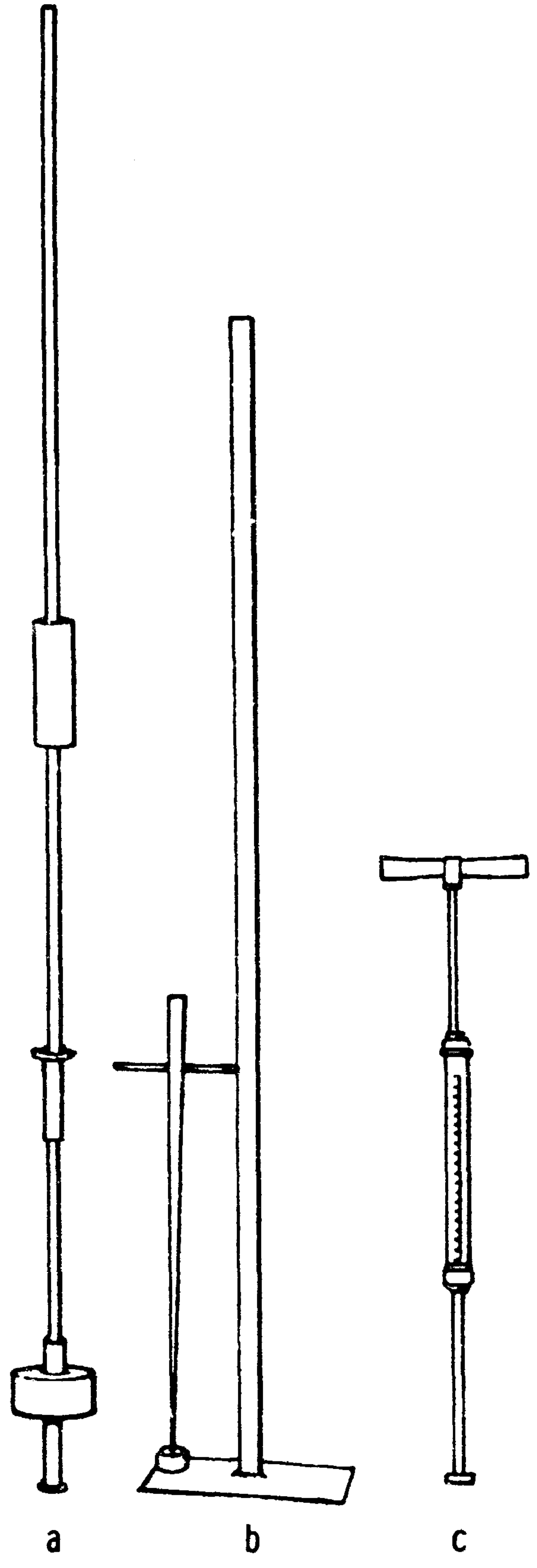

Figure 5 McKibben's (1940) collection of soil esting instruments:
a) Iowa penetrometer; b) Rototiller penetrometer; c) Proctor's plasticity needle

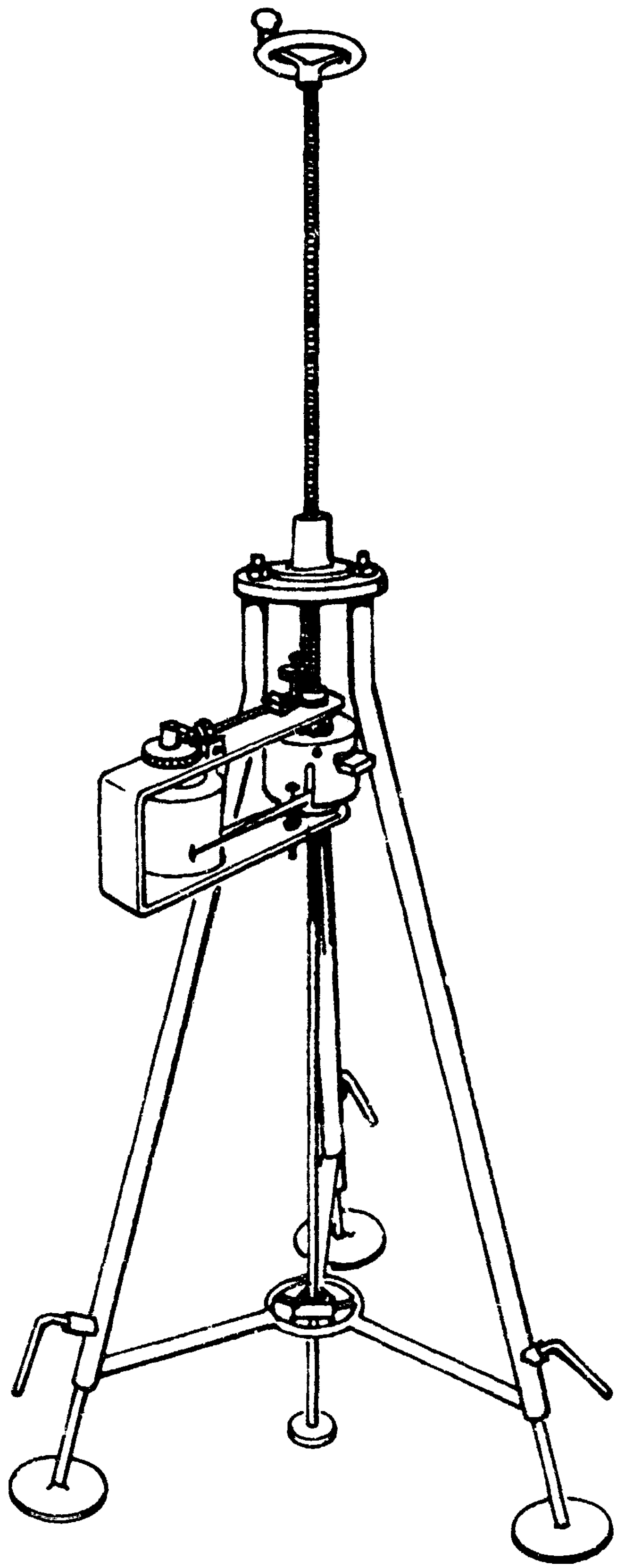

Figure 6 British AORG constant rate portable penetrometer (ORG 1947)

Using the idealized Pradtl solution for load-deformation process, they attempted to measure in soil those properties which would fit Pradtl's premises. This obviously could not be achieved. Thus they concluded "further investigation into the properties (of the instrument) was needed."

Whatever investigations were performed later, they have not yet provided a permanent place for a single small-plate penetrometer in off-road locomotion research, as will be shown further on these pages.

Amazingly enough, agricultural engineers never gave up working on penetrometers of this type. Perhaps some of their problems may find a solution, if phenomena such as root penetration and elongation, soil permeability, relative soil strength profiles in tillage, etc., can be correlated with the load-penetration curve of an arbitrary plunger. Apparently they hope this can be done. For with this hope, Hendrick (1969) proposed in the United States a device very much like the old fashioned instrument shown in Figure 6. His excellent bibliography, however, did not go far enough in order to at least quote that the AORG (1947) had developed a similar, if not identical, instrument 22 years before.

Revyakin's Plate Penetrometer (1950?)

This instrument was often mentioned by various investigators. Apparently it was a standard piece of equipment, because no specifications or date of introduction were found by this writer. Following Kosharnyi's (1966) remark it must be assumed that the penetrometer was a rather sizeable apparatus that used round penetration plates of the size of the ground contact area equal to the size of the prints of tires under investigation.

Zaleski (1956) reported the same instrument under the name Goryachkin-Revyakin penetrometer, using round plates and recording load sinkage up to the depth of 30 cm.

It appears that the main tool for soil measurements in Russian agriculture in the fifties was the Revyakin penetrometer, which was also called the Goryachkin. The DORNII penetrometer found application only in civil engineering.

In the Goryachkin-Revyakin penetrometer, the value of soil hardness was obtained from a probe 30 cm deep. A single value, proportional to the angle of slope of the load-penetration line, was considered as an "index." But most often the test showed that the line was not straight, and the determination of the "modulus of deformation," which really was measured, became tricky. Thus Zaleski (1956) came forward with the idea that the area underneath the load-penetration line be taken as proportional to the "index," and not the variable slope. But he was puzzled with differences caused by various flat plates, cones, and ball tips. As a result, the Leningrad Institute of Mechanization of Agriculture (Zaleski, 1956) devised an involved method for soil "indexing" with penetrometers, which is of little consequence in the present context because it did not apply to locomotion.

Tsymbal Rotating Penetrometer (1958)

The Russian problems with the penetrometers, as seen on the background of confusion in other countries, understandably became intolerable. The empirical correlation between a simple arbitrary index (with an arbitrary method) and the trafficability or tillability of soil was recognized as unattainable.

Hence, Tsymbal (1958) of the All Russian Research Institute for Mechanization and Electrification of Agriculture (Rostov Region) came forward with an idea of a rotary penetrometer for:

> "determining those physico-mechanical properties of the soil which are necessary for evaluation of soil as engineering material, and as a supporting* medium for agricultural equipment and tractors."

He claimed that his instrument may determine:

- force of penetration resistance
- "specific force" of soil shear
- coefficient of soil-metal friction
- coefficient of soil-soil friction
- Letoshev's modulus of soil deformation, k_L, in wheel rolling resistance equation.

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* Note the word "supporting."

Without attempting empirical correlation of the above soil values with vehicle performance, Tsymbal maintained (without explanation) that when

> "using these parameters it is possible with the help of equations of agricultural mechanics to make calculations of the technological process of soil working tools and wheel travel..."*

What a departure from the previous guessing game in devising the instrumentation of soil measurements! The fact that Tsymbal's premises were impractical, and that his apparatus did not work as expected, does not belittle the significance of this first switch from purely empirical to more theoretically warranted instrumentation.

The same trend was marked earlier in the Canadian-American research by the publication of the first outline of a rational soil-vehicle measuring philosophy (Bekker, 1950, 1955, 1956, 1957). This outline was carefully recorded in the Russian literature, in contrast to a traditional poor referencing of foreign authors.

The most significant feature of Tsymbal's new instrumentation was the measuring of "specific force" of soil shear, and soil-to-soil friction. These measurements were undoubtedly added to the penetration test, through the influence of contemporary American work performed by the Army's Land Locomotion Laboratory in Detroit. Significantly the Waterways Experiment Station also added shear tests to their "cone" test, almost at the same time.

The scheme of Tsymbal's apparatus is shown in Figure 7. The details are unclear but the general principles of operation are easy to understand. Crank 1, actuating bevel gears 2 and screw 3, forces into the ground penetrometer rod 4 tipped with cone 5. The crank also rotates the cone when the latter penetrates the ground. Spring gauges and a rather poorly depicted system of levers and threads constitute the recording systems for the torque, penetration, and vertical force. Drum 6 feeds paper for the torque-force-sinkage record obtained by means of pens 7 and 8.

The k_L-value was determined by using a "special standard wheel," 9, which was rotated on arm 10. The arm was then clamped in position to rod 4, and the rotating torque T_W was recorded on the paper tape by means of the same mechanism which

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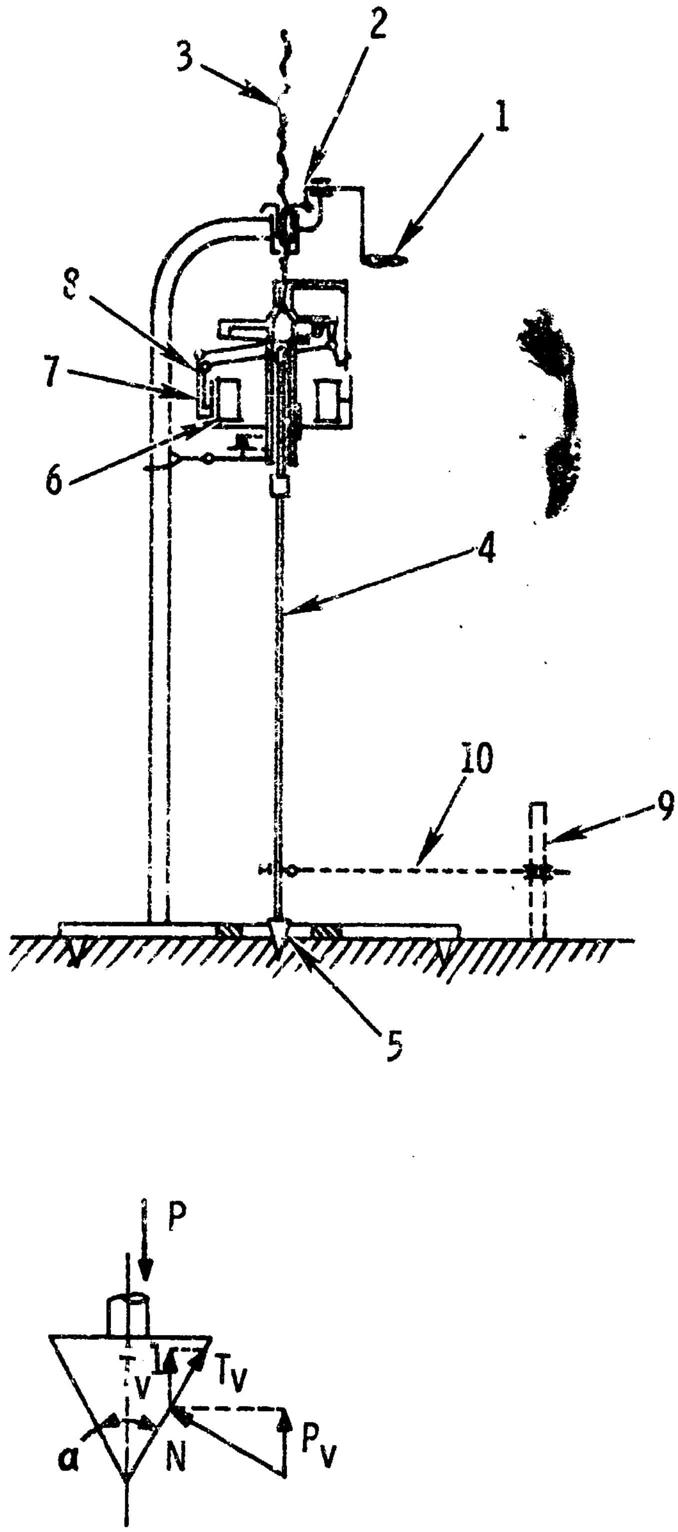
* Underlined by the present author.



(a)

Figure 7 Tsymbal's (1958) rotary penetrometer with "standard" wheel measuring Letoshnev's k_L.

recorded torque of the rotating cone. Motion resistance of the "standard wheel" was calculated from $R = T_W / r_a$, where r_a was the length of arm 10. k_L was then determined from equation (69):

$$k_L = \left(\frac{\alpha}{R}\right)^3 \left(\frac{W^4}{r_a{}^2 b}\right) \tag{69}$$

The penetrometer itself was called by Tsymbal the "Goriachkin penetrometer," which implies that the latter used a rotating cone. In penetration, the following forces were assumed: P-penetrating force including a part of the instrument weight; P_v-vertical component of N; N-normal reaction to cone surface; T_v-frictional force on cone surface equal to $N\mu_o$; T'_v-vertical component of frictional force T_v (Figure 7a). Accordingly:

$$P = P_v + T'_v = 2N \sin(\alpha/2) + 2N\mu_o \cos(\alpha/2) \tag{70}$$

Frictional forces caused by cone rotation were accounted similarly from equilibrium of forces involved in cone rotation. Thus the coefficient of friction μ_o of metal on soil could be determined from the torque and the penetrating load record. Coefficient of "soil shear" was determined by using a "ribbed cone."

The mathematics of equations developed by Tsymbal for the purpose of calculating all these values was extremely sketchy. In addition this author had to work on an English translation of the original work that appeared to be inaccurate. It produced dimensionally inconsistent equations, in a rather disorderly manner, lacking clear denotations. Although the necessary equations could be independently reproduced, the work involved was not considered worthwhile, because further information about the use for locomotion of Tsymbal's instrument was not found by this writer. Undoubtedly, the idea never caught up with practice.

Rokas' Rotating Penetrometer SSG-3 (1960)

The idea of rotating a penetrometer, however, was not totally forgotten. It was revived as a new concept by Rokas (1960), almost within the same frame of thought as that originated by Tsymbal (1958). The main difference consisted of four vanes attached to the cone, Figure 8, which were used instead of the "ribbed cone."

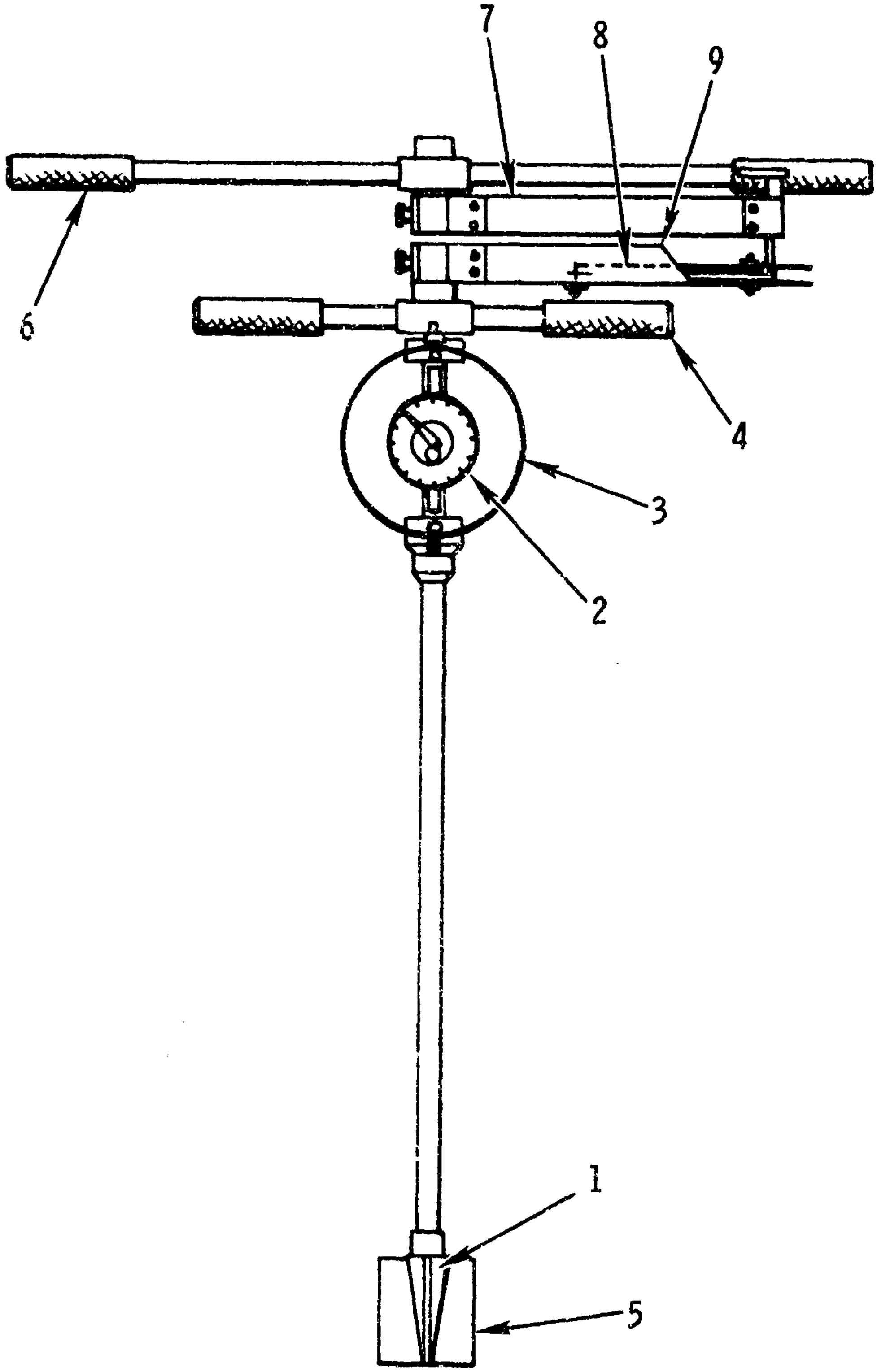


Figure 8 Rokas' Rotating Penetrometer (Rokas 1960)

The instrument was built at the Moscow Highway Research Institute (MADI). Conical tip 1 had a 30° angle and 5 cm^2 base. The dimensions of vanes 5 were not given. Dial 2 indicated the load $\Psi_2(p)$ on spring 3 (and cone 1) imparted manually through handles 4. Upon forcing cone 1 with vanes 5 into the ground, the operator rotated the instrument by means of handles 6. Spring 7 deflected proportionally to the torque actuated pointer 8, which showed the torque $\Psi_1(\tau)$ on scale 9.

This was an exact copy of the WES cone penetrometer and the British shear vane (Figure 9a and b) combined in one instrument. What WES and the British civil engineers hoped to achieve separately, Rokas tried to materialize in this hybrid solution. His goals, however, were less ambitious than Tsymbal's, for he did not propose to use equations of applied mechanics, as Tsymbal did, in order to predict vehicle performance and design parameters. Instead, he used the instrument "indices" $\Psi_1(\tau)$ and $\Psi_2(p)$ (see Chapter II) as a means for empirical correlation with unit motion resistance and drawbar pull of existing vehicles.

Evaluation of $\Psi_1(p)$ and $\Psi_2(\tau)$ was performed for various soils and soil conditions, assuming simple relationships between pressure (p), shear (τ) and the dimensions of the cone-cum-vanes penetrometer:

$$p = \frac{P}{\pi h^2 \tan^2(\alpha/2)} \tag{71}$$

where h is the height of the cone and P the load shown on dial 2 (Figure 8).

$$\tau = \frac{T}{C} \tag{72}$$

where T is torque measured on dial 9 (Figure 8) and C has a value of C_1 when the cone penetration equals cone height h:

$$C_1 = \frac{\pi d^2}{2} \left(\frac{d}{6} + h\right). \tag{73}$$

For penetration larger than cone height h:

$$C_2 = \frac{\pi d^3}{12} + \frac{\pi d^2 h}{2} + \frac{\pi}{16} (d^2 - d_c^2)(d - d_c) \tag{74}$$

where d is the diameter of the vane circumference and d_c is the diameter of cone base.

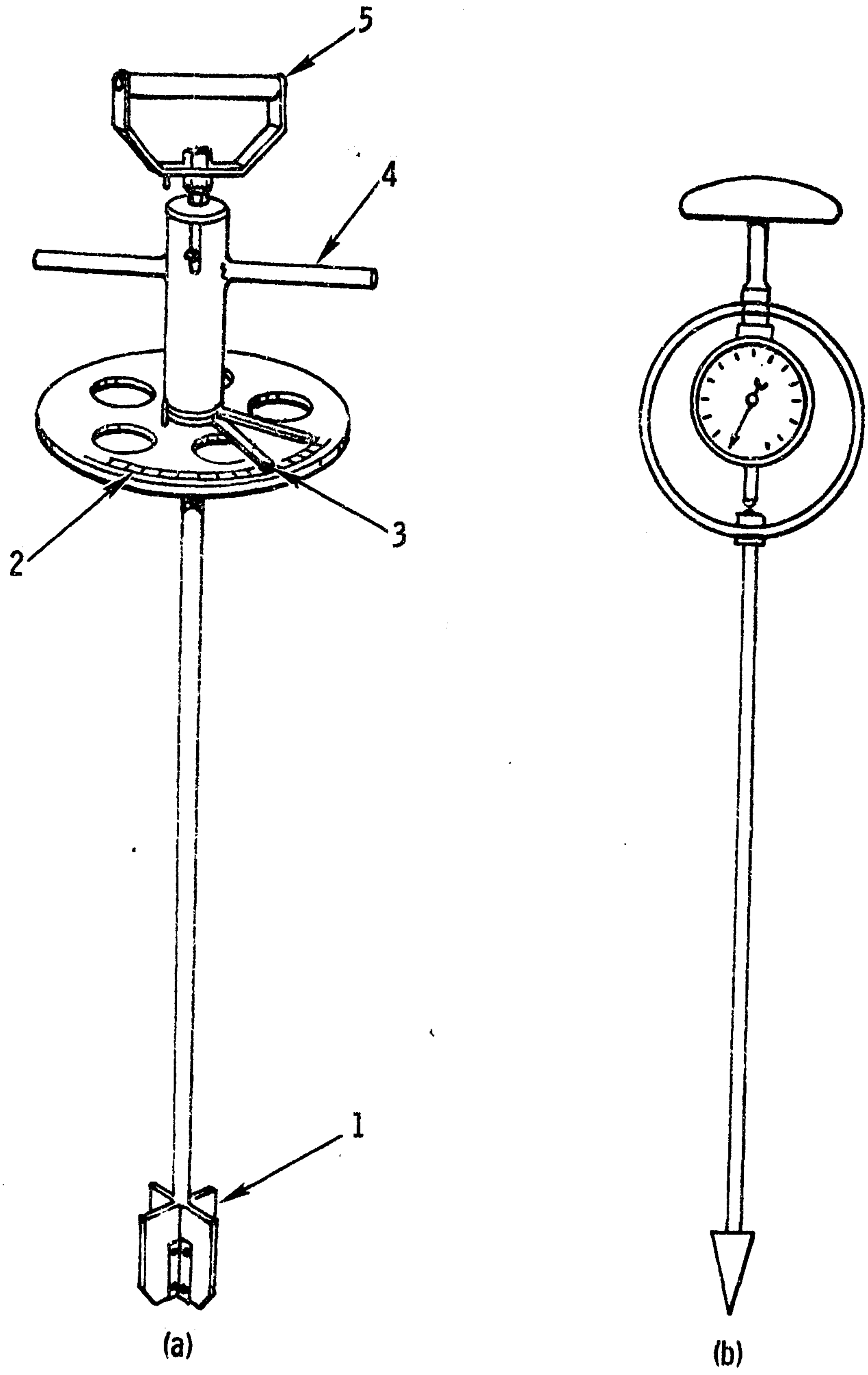


Figure 9 a) British Shear Vane AORG (1948) and
b) WES Cone Penetrometer (ca 1942)

Results of measuring p and τ in various soils were reproduced after Rokas in Figure 10. The graph shows extrapolated straight lines without displaying the unavoidable scatter of measurements, which makes it difficult to judge the accuracy of the method; it was reproduced here for whatever it is worth: 1 - dry river sand; 2 - fine wet sand; 3 - sandy fine grained soil; 4 - grass covered light soil and muddy meadow; 5 - "black" clay (?).

Attempts to correlate unit drawbar pull with $\Psi_1(\tau)$ and unit motion resistance $\Psi_2(p)$ of truck GAZ-63 with 2 ton load, equipped with 9.75 - 18 tires led to the graph, Figure 10b. Note that the graph is not accurate and Π is not exactly equal to $\Pi = \Psi_1(\tau) - \Psi_2(p)$, although the error seems to be constant. Tests were performed on grassy terrain composed of loose soils, turf meadows, and wet or humus soils with dense grass cover.

The variety of soil types and the smallness of the instrument reportedly produced a great scatter to the penetration depth of 30 cm. However, as the author claims, the coefficient of correlation achieved between mean values of p taken at various depth and unit motion resistance of the truck was 0.84 to 0.86.

The tests included the study of speed effect of the shear and penetration upon values of p and τ. The result was negative for practical purposes.

Rokas recommended a minimum of 15 to 20 soil measurements for acceptable reliability of correlation with one vehicle performance datum.

Further illustration of correlation of Rokas' (1963) "indices" $\Psi_2(p)$ with unit motion resistance f of a truck MARK ZIL-157 was shown in Figure 11. Points 1 correspond to dry, medium fine sand; points 2 refer to wet fine sand; 3 to fine sandy arable soil; 4 to turf soil with grass cover on a wet meadow.

Everything looks all right. But anyone familiar with the error involved in the measurement of f and the error of evaluation of p must agree that differences shown in Figure 11 between f, for 1.5 and 3 atm. of inflation pressure, are undetectable; and the difference between 0.5 and 3 atm. show too small a variation of f in order to be taken as quantitative indication of change of motion resistance. To see this, it is enough to superimpose the graphs of Figure 11, without going into statistical evaluation of error.

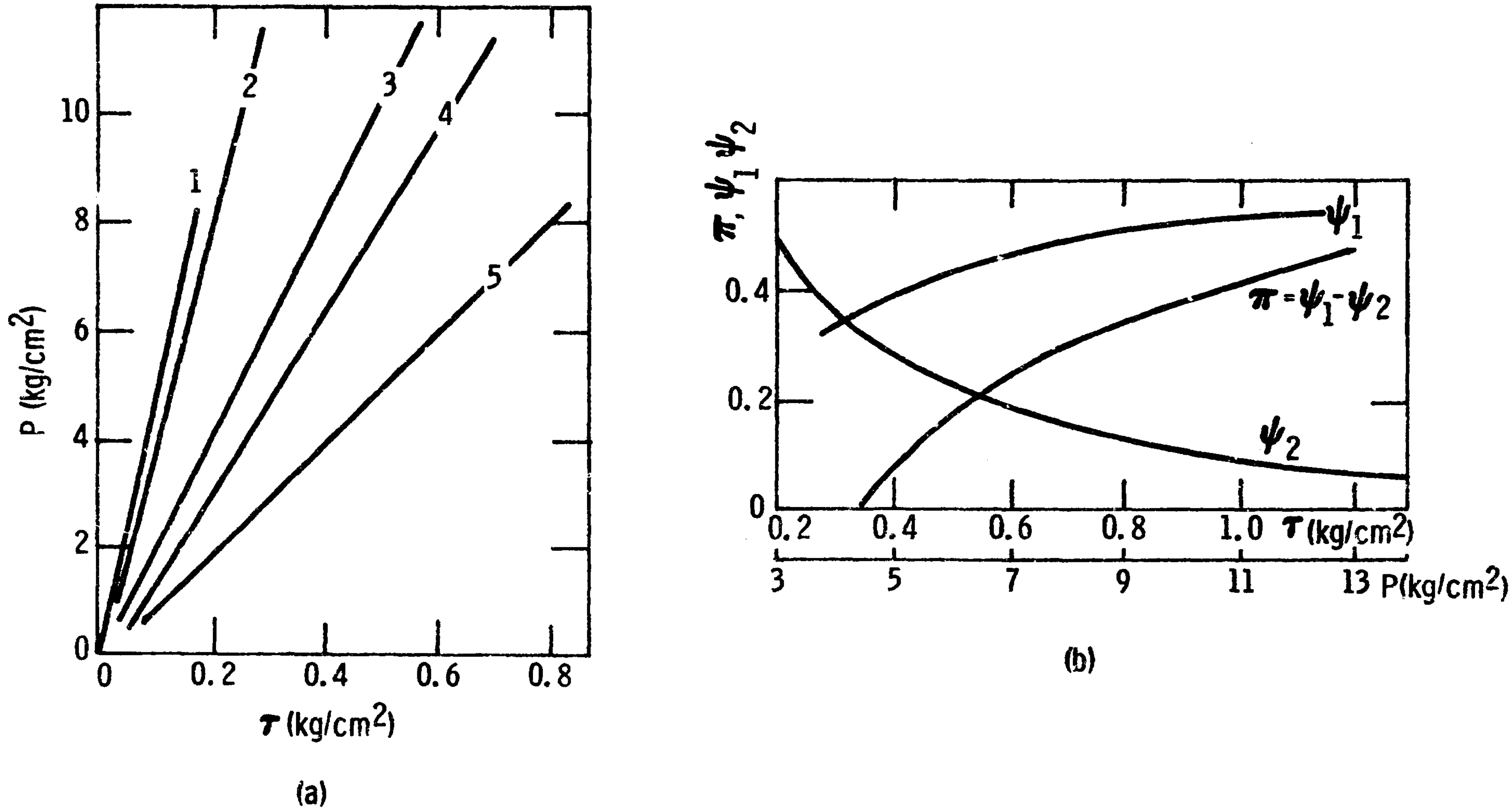


Figure 10 Rokas (1960) measurements of soil "indices" (a) and their empirical correlation (b) with "go - no go" performance π, unit drawbar pull Ψ_1 and unit motion resistance Ψ_2; ($\Psi_1 \Rightarrow DP/W$; $\Psi_2 \Rightarrow R/W$).

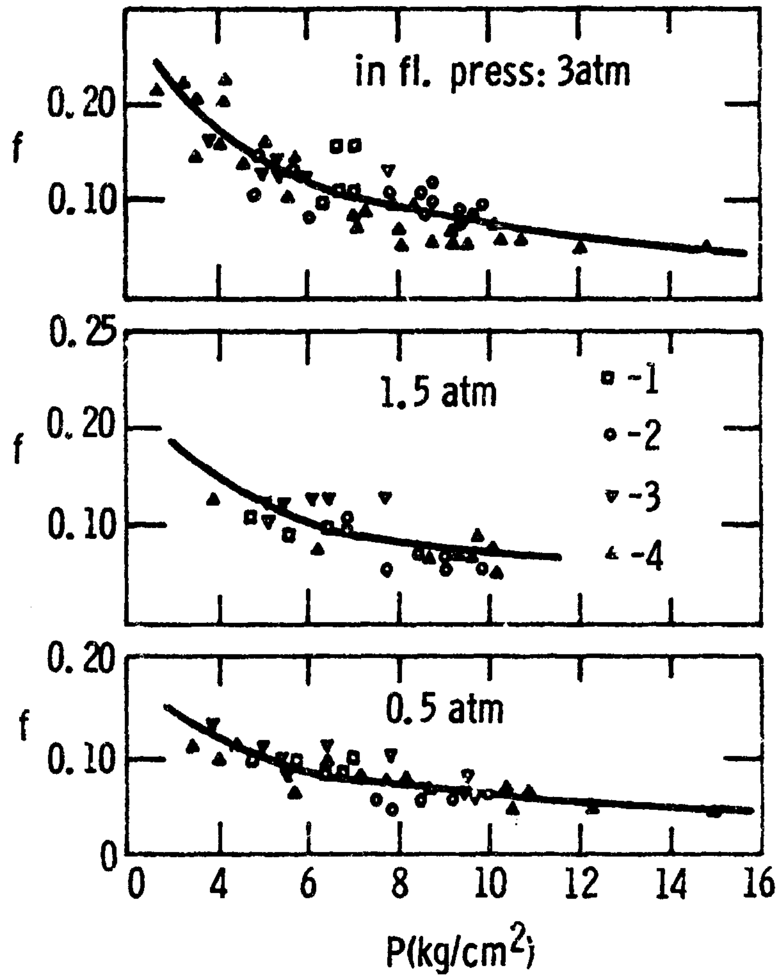


Figure 11 Rokas (1963) index p versus unit motion resistance truck ZIL-157 for various inflation pressures (tires 12. 00 - 18) in various soils

Thus Rokas' instrument only shows the right trend but not the quantitative differentiation between soil-vehicle interactions that he sought to define for practical purposes. No further use of this method was encountered.

ASHN-BSSR Penetrometers (1960 to 1961)

The Bieloruskii Institute for Mechanization and Electrification of Agriculture in Minsk used a flat-plate penetrometer for a long time, which was identical in principle with Mayer-Bernstein and other derivatives of that instrument. This was a non-recording, dial-type device for a quick identification of soil primarily for agricultural, non-locomotion purposes, Figure 12 (Katsygin and Aziamova, 1960).

The device, approximately 1 meter high, probed the ground to the depth of 5, 10, 15, and 20 cm. Flat penetration plates of diameters 1, 2, 5, and 10 cm^2 were standard equipment. The dial had a pointer which stayed at the maximum load, at the given depth. The instrument weighed 4 kg.

"For determination of bearing strength of soil, besides circular penetration tips, three cones 40, 40, and 20 mm high, having angles of 30, 40 and 30^o, respectively, may be used," Figure 13. According to Katsygin and Aziamova (1960), the cones enabled one to determine not only the k_{co}, and n values of a quasi Letoshnev equation, $p = k_{co} \Delta^n$, but also metal-to-soil friction μ_o. Δ-value here was not the sinkage but the soil displacement perpendicular to cone surface, as shown in Figure 13.

Matsepuro and Runtso (1961) produced the mathematics to calculate k_{co}, n, and μ_o values. The procedure was based on integration of elementary forces τ and δ along the cone surface F. Elementary friction force $\tau = \mu_o \delta$ which comprised the value of the coefficient of friction μ_o was included in the dial reading of the total penetrating force P (Figure 13). The final equations and the procedure of using three cones in order to determine the three unknowns were briefly described in Chapter II (see Equations 42, 43, 44). Alignment charts for a quick calculation of these parameters were given in both references by Katsygin, Aziamova, Matsepuro, and Runtso, though not with the same precision.

Note that the described instrumentation, Figures 12 and 13, was included in the chapters of the "Voprosy ...," which was not concerned with locomotion but with ploughing and

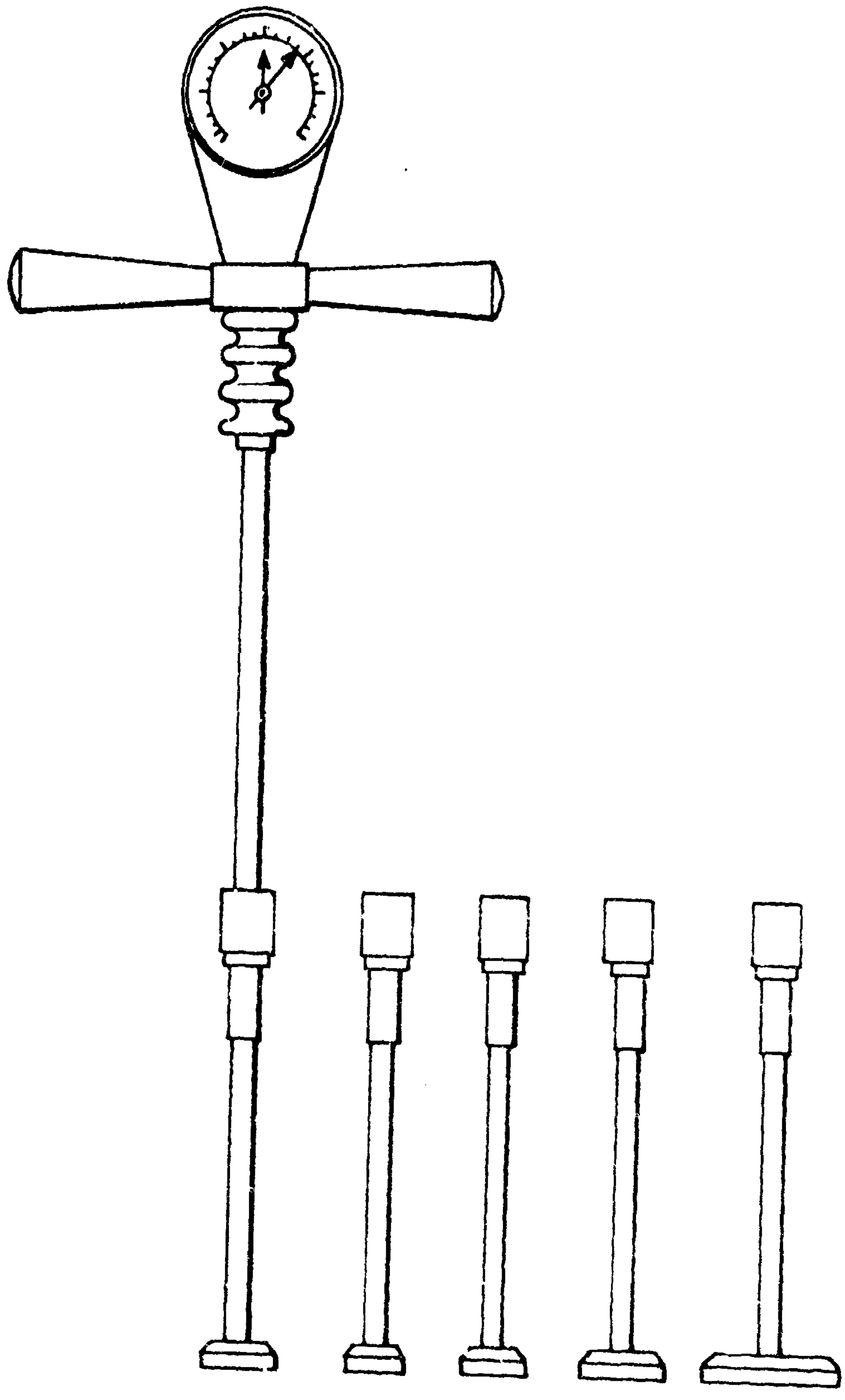


Figure 12 ASHN-BSSR Penetrometer (Katsygin and Aziamova, 1960)

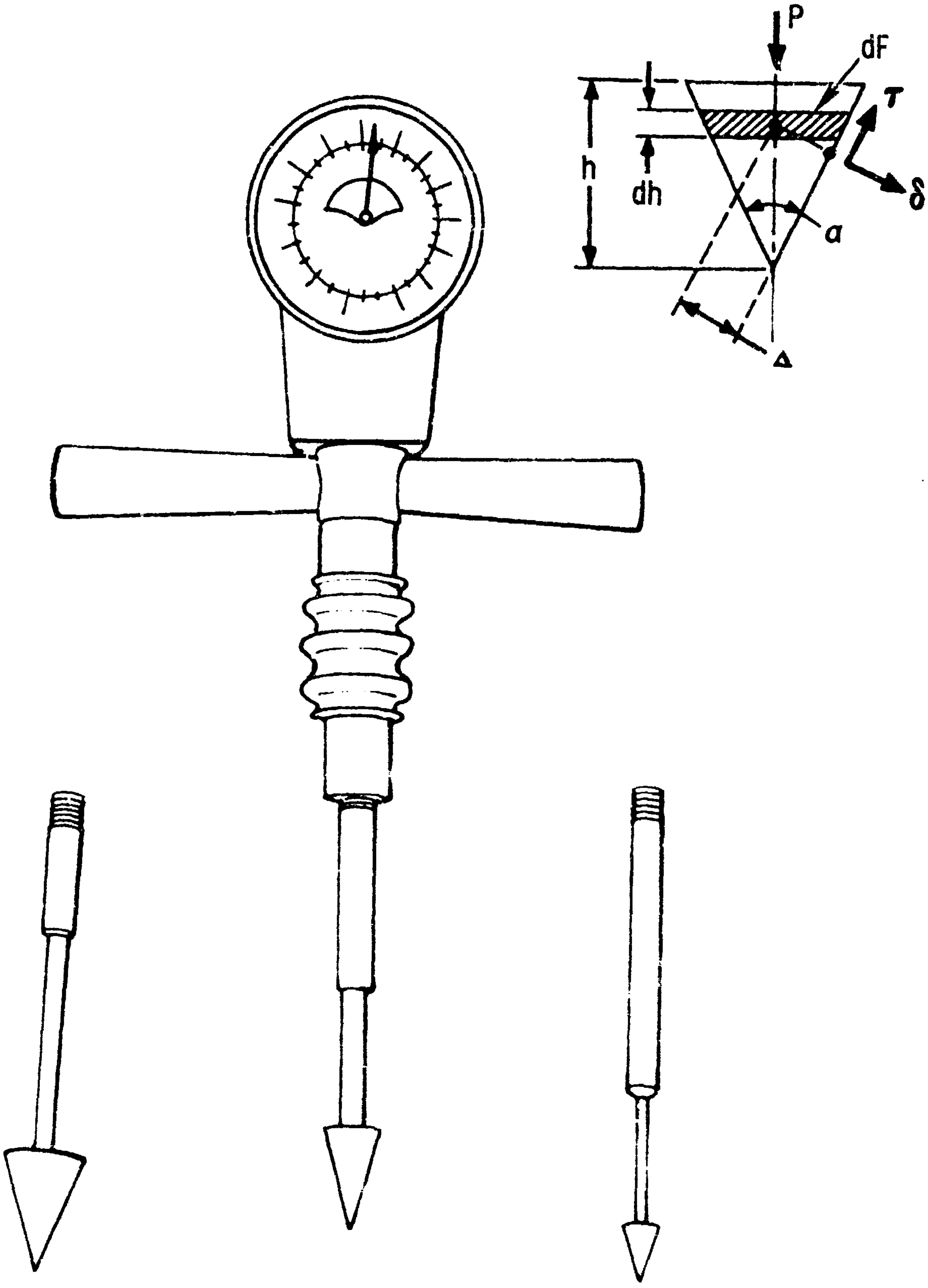


Figure 13 ASHN-BSSR Penetrometer (Katsygin and Aziamova, 1960)

general soil testing. There was no indication that these penetrometers were used for locomotion.

A comparison between plat plate (Figure 12) and cone penetrometers (Figure 13) leads to interesting conclusions. The flat-plate test led to determination of Letoshnev's k_L and n-values, according to the old formula:

$$p = k_L z^n$$

The three-cone penetrometer produced similar soil parameters plus one more value, the coefficient of soil-to-metal friction μ_0, in addition to the quasi-Letoshnev penetration values defined by slightly the modified equation:

$$p = k_{co} \Delta^n \qquad (75)$$

It thus appears that it was the search for μ_0 which spurred the three-cone concept, undoubtedly under the influence of Tsymbal (1958), who was the first to produce μ_0 with one cone – by rotating it during the penetration. If this conclusion is correct, the battle of ideas between Rostov and Minsk Agricultural regions was obvious, as the latter did not mention Tsymbal.

An impartial observer may note, however, that the measuring of μ_0, which is all important in ploughing and tilling, may be accomplished by simpler means than rotating a cone or penetrating the soil with three cones.

Boychenko Penetrometer (1960)

It seems that the Russian soil researchers concerned with agricultural problems attempted to "improve" the existing foreign devices, rather than to replace them with their own. This is well illustrated on the so-called Boychenko penetrometer (Katsygin Ind Aziamova, 1960). This instrument was used only in the laboratory for determination of plasticity indices, and had no direct application to locomotion.

Boychenko and his followers wanted to replace the semi-qualitative measure of soil-sample strokes, in Atteberg test, with a more accurately defined procedure. To this end they tried an elaborate process in which the soil plasticity was tested by cone penetration. The results are unknown and further references are lacking.

Bernacki Penetrometer (1960)

Bernacki (1960), of the Polish Institute of Mechanization and Electrification of Agriculture, did not quote Boychenko, but his soil penetrometer used an almost identical and elaborated nonius scale for sinkage measurement, and outwardly looked like Boychenko's laboratory equipment. He seems to have started from scratch, however, when trying to develop a mathematical relationship of the soil-machine interface, including locomotion. Complaining about the lack of data on load-deformation characteristics of soil, he quoted only two Russian references (Krutikov, 1951; Lvov, 1952) which really did not say much in that respect; and without mentioning Bernstein or Letoshnev he applied their formula for a peculiar case of $n = 1$:

$$p = k_L z$$

Bernacki's penetrometer is shown in Figure 14. Tube 1 slides inside tube 2 which is supported on the ground by tripod 3. The upper portion of tube 1 had a loading platform 6. Scale 4 moved with tube 1. The nonius-caliper attached to the upper part of tube 2 gave accurate readings of the sinkage of penetrometer plate 5.

Since no single penetration value could be obtained, Bernacki tried all kind of penetrometer heads, as shown in Figure 15. Data obtained with various soils were shown in Table 14.

Kuznetsov Rotating "Durometer" (1962)

Kuznetsov (1962) observed that penetrometers do not reproduce working relationship between machines and the soil. Accordingly, "the principle of vertical and horizontal deforming of soil" was introduced in his instrument, shown in Figure 16.

The basic concept was not new. It was first introduced by Bekker (1948, 1950), adopted by Weiss (1952), and finally incorporated in a modified form into the bevameter technique (Bekker, 1955, 1960 and 1969). Kuznetsov, who worked for the Kuibyshev Agricultural Institute, did not produce in his paper any references. He even failed to mention Tsymbal (1958) and Rokas (1960) who, after all, utilized "vertical load" and "horizontal shear" as soil indices.

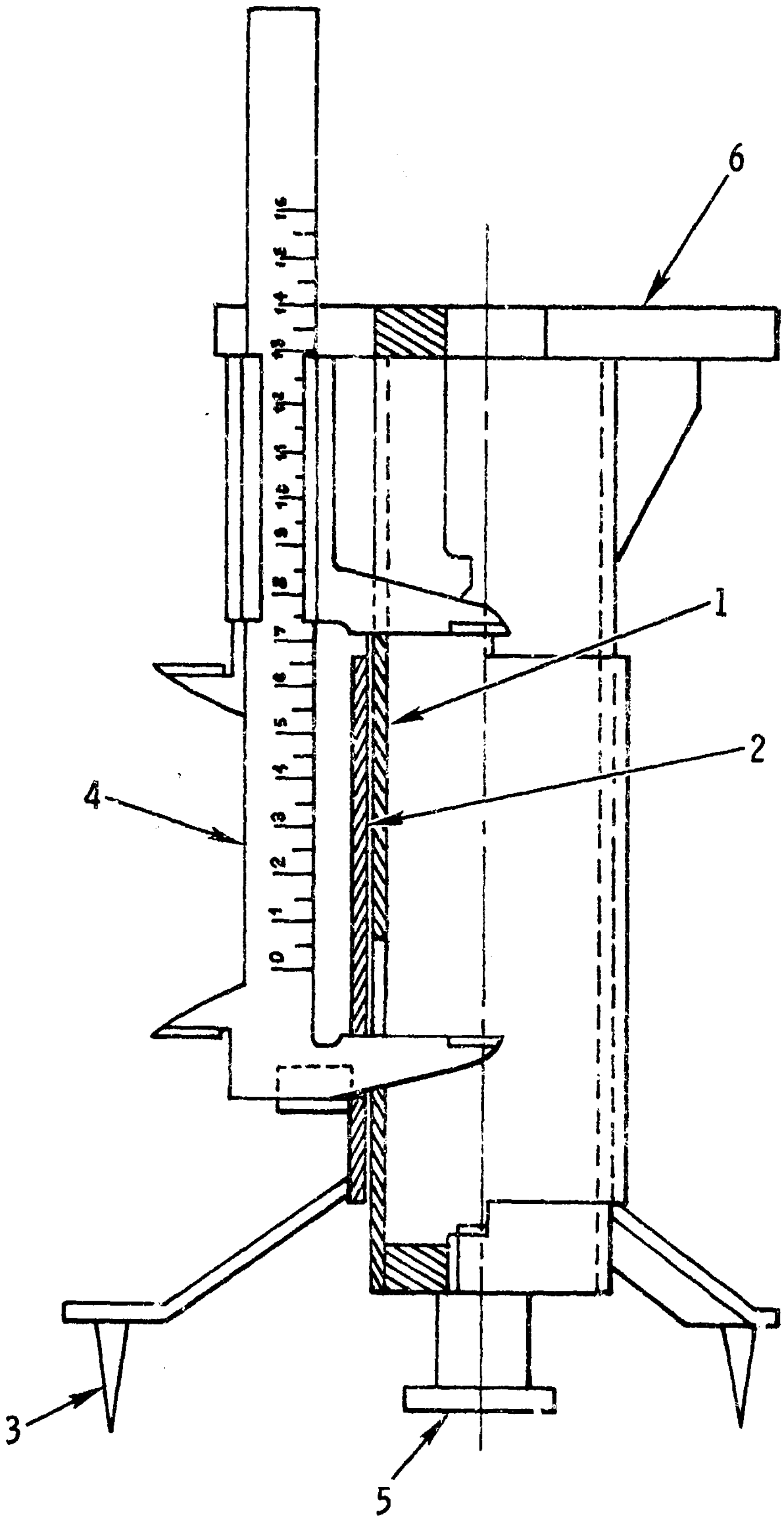


Figure 14 Bernacki (1960) Soil Penetrometer

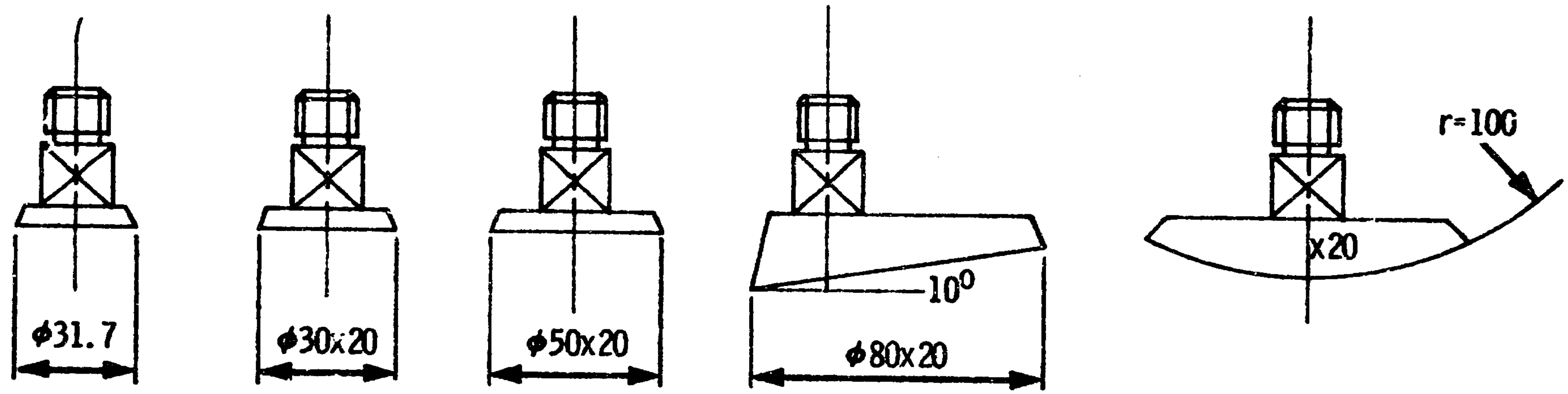


Figure 15 Bernacki (1960) Penetrometer Heads

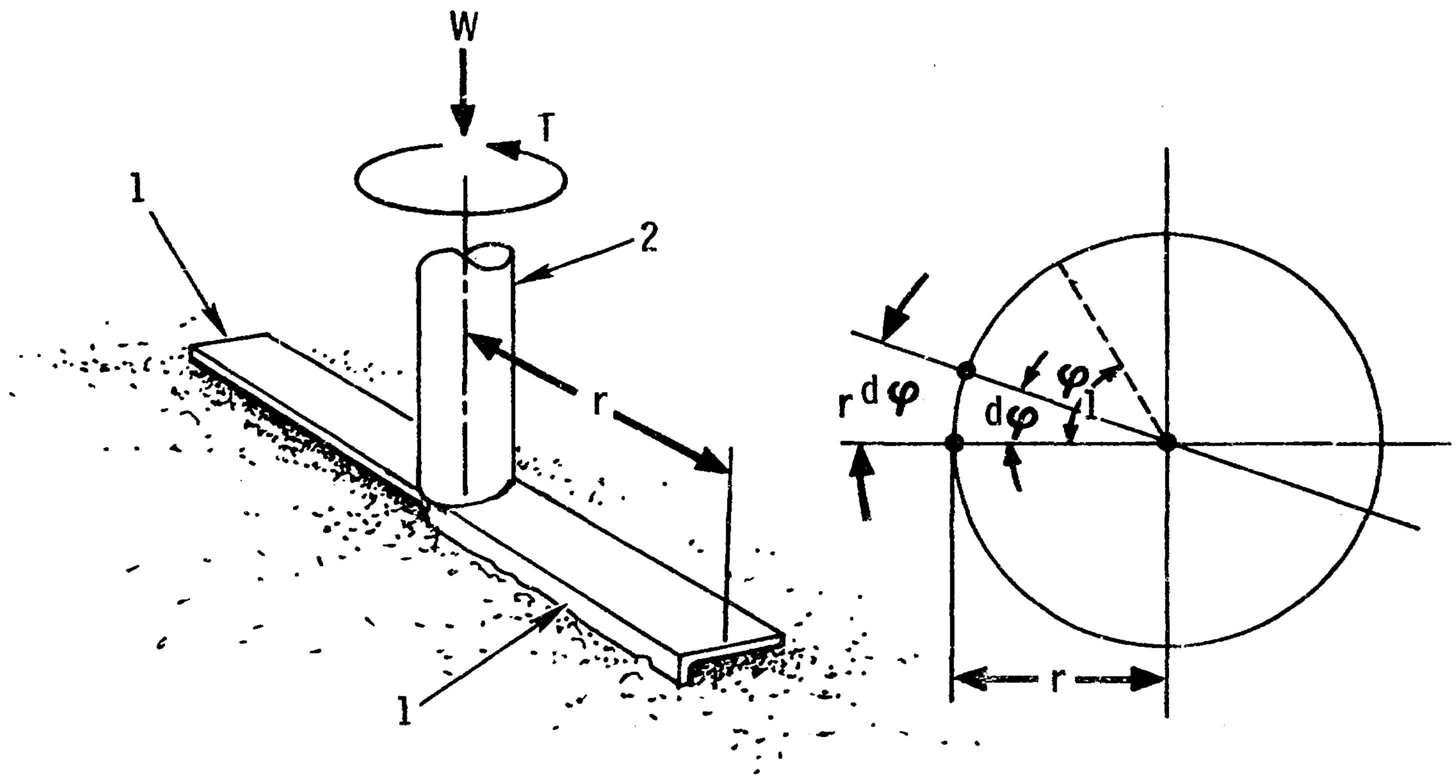


Figure 16 Kuznetzov (1962) "Durometer" provided shear under vertical load

Kuznets[illegible]s du[illegible]ometer, [illegible]s he [illegible]lls it (Figure 16 was co[illegible]osed [illegible] two angular blades (1) which were rotated by shaft 2 under vertical load W. The soil value was defined in the following manner: assume that "ground hardness" Γ (kg/cm^2) is directly proportional to soil deformation work E_o (kg cm) and inversely proportional to the deformed volume V (cm^3)

$$\Gamma = E_o/V \tag{76}$$

If torque Γ exercised on the vertical shaft 2 is needed to shear the soil by angle $d\varphi$, then:

$$dE_o = \Gamma \, d\varphi \tag{77}$$

The volume of deformed soil is then:

$$dV = (r^2 h/2)\, d\varphi \tag{78}$$

where h is the height of the vertical flange.

Deformed soil volume V is:

$$V = \frac{r^2 h}{2} \int_0^{\varphi 1} d\varphi = \frac{r^2 h \varphi_1}{2} \tag{79}$$

and the work of deformation E_o is:

$$E_o = \int_0^{\varphi_1} T\, d\varphi = T\varphi_1 \tag{80}$$

Substituting equations (79) (80) in equation (76) ground "hardness" was expressed by:

$$\Gamma = \frac{8T}{hd^2} \tag{81}$$

where d = 2 r.

Γ-value was related by Kuznetsov through Goriachkin's equation to the unit resistance of the plough. The whole idea was not tried in locomotion. The described instrument was another gadget aimed at establishing index Γ, which would enable one to predict

plough draft. The instrument had diameter d = 69 mm. Surprisingly, Revyakin's penetrometer also was used with a flat head having the area of 1 cm^2. This implies a somewhat loose or incomplete procedure. Since this procedure was applied only to plough performance prediction, it will not be described further.

However, the similarity of the Kuznetsov instrument to some of the U. S. instruments used for locomotion purposes under different premises (Bekker, 1948; Weiss, 1952) is worthwhile noticing as a historical curiosity.

Soil-Meter SKB - MGU (1964)

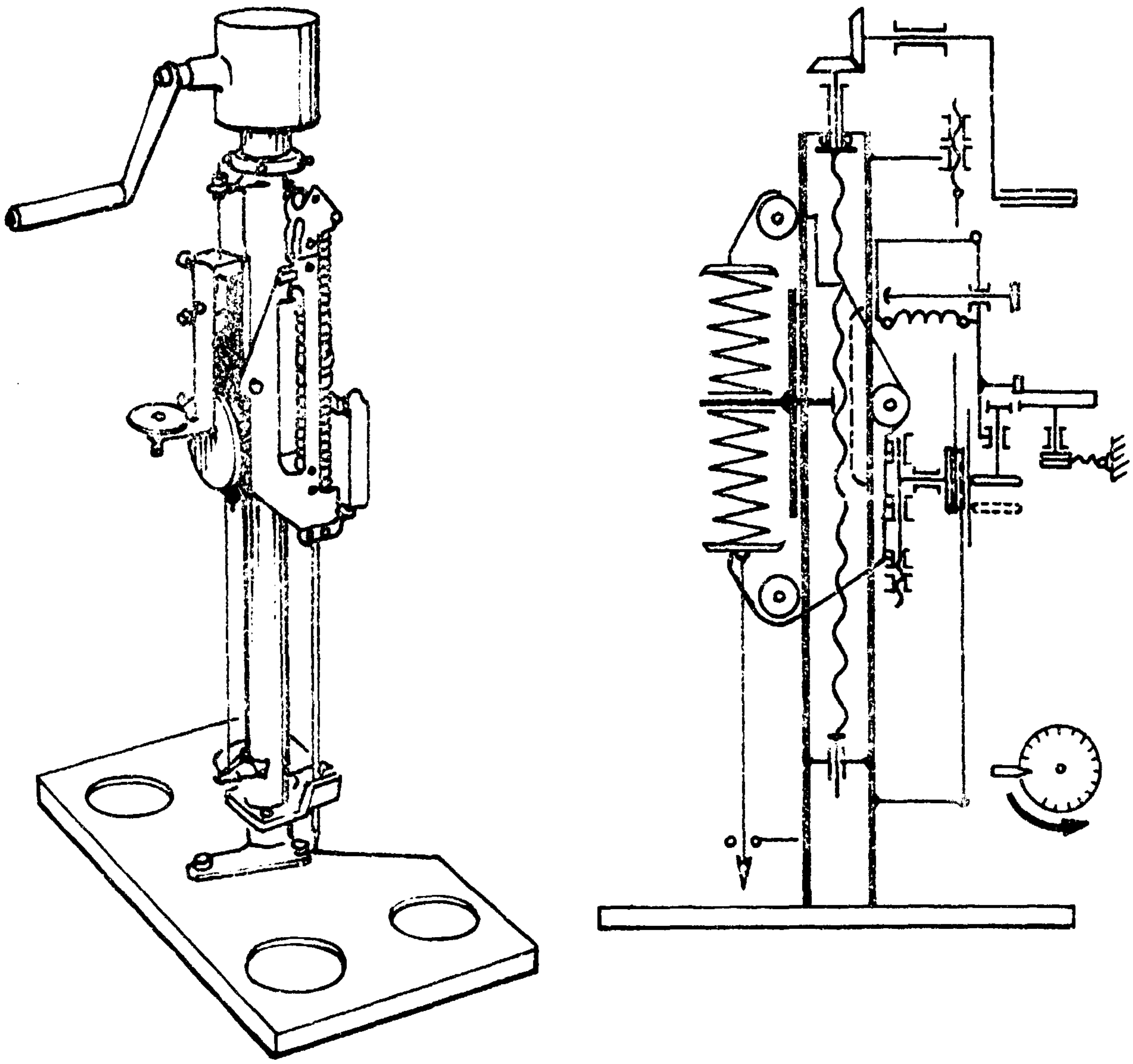
This instrument was mentioned by Kudinov (1964). Details are lacking. It records "penetration resistance" in kg/cm^2.

Soil Measuring Devices, Improvement by VISHOM (1965)

While some inventors were trying to come up with newer and newer gadgets for soil measurements, others tried to improve the existing ones. Engineers at VISHOM, for instance, were not satisfied with orthodox data processing methods and statistical evaluations (Regulations GOST 2911-54 for field testing of agricultural machinery). In order to obtain quickly mean values and to smooth out irregularities in soil penetration and friction tests, they developed mechanical "integrators" composed of a series of frictional discs and gears.

One of these devices applied to a penetrometer is shown in Figure 17 (Vysotskii, 1965), which displays the general view. Figure 17b purports to depict the mechanical detail which is not proposed to be followed, even in a crude approximation, because of the obscure drawing and description available.

Similar "integrators" were tried for instruments measuring soil-to-metal friction, Figure 18. Vysotskii criticized devices that use discs (Figure 18a) under load W, which when rotated require torque T to overcome friction F. He also did not like Tsymbal's rotating cone (Figure 18b). As a result the VISHOM engineers devised a rotating ring (Figure 18c), which is just a variant of a bevameter ring applied to measuring metal-to-soil friction. The "integrator" box shown in the upper portion of Figure 18 incorporates the ring.



(a) (b)

Figure 17 VISHOM "Penetrometer with a Mechanical Integrator" (Vysotskii, 1965)

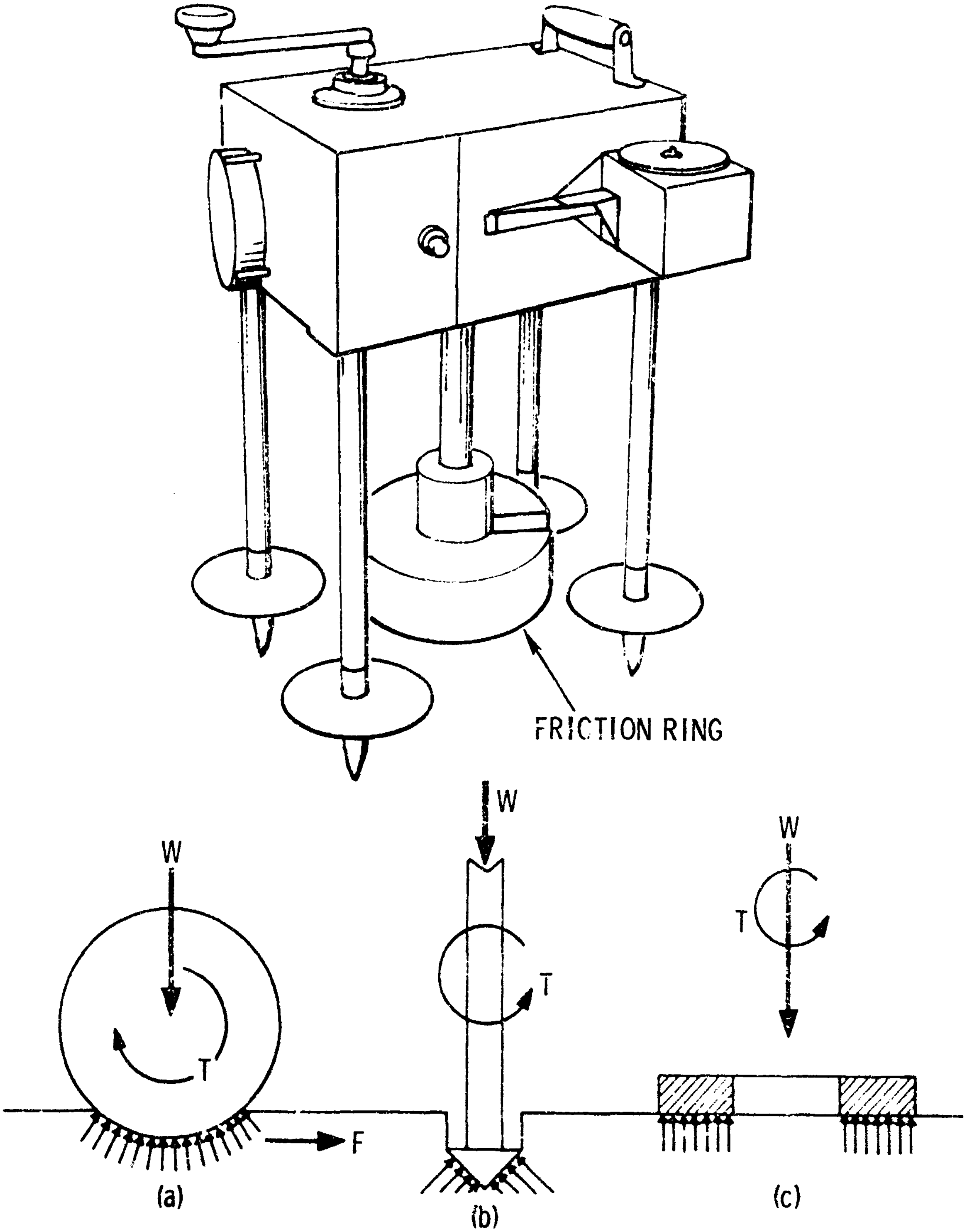


Figure 18 Soil-Metal Friction Measuring Device with VISHOM "Integrator" (Vysotskii, 1965)

Considering that these developments were taking place before 1965, and still utilized clumsy mechanical, instead of electronic, systems, it may be agreed that the state of the art was not well advanced. Electronic data recording and processing was used in the U. S. with bevameter techniques long before that time.

In addition, the preoccupation of some Russian agricultural engineers with the small tactics of instrumentation, when the broad strategy of research remained undefined, does not seem to imply much planning of the team effort.

Penetrometer Minsk, (1962)

Instead of gadgets and arbitrary indices, Matsepuro and Hao-Sin-Fan (1962) used a regular recording, flat-plate penetrometer, Figure 19.

In a study of design and performance of tracked tractors, they reproduced Bekker's (1956) explanation of the relationship between slip and track length, following a rather complex mathematics of soil-track relationship of their own. The instrument described in this analysis (Figure 19) served the purpose of investigating the effect of duration of the loading time upon soil deformation. Penetrating plate 1 was forced into the ground by the weight of container 2 loaded with unspecified weights.

The plate-loading process was starting instantaneously and lasted as long as required. This was achieved by suspending the load by means of wire 3, which was cut at the desired moment and then reinstated for lifting the load. Load-sinkage performance was recorded on paper drum 4. The apparatus was mounted on stand 5.

No details regarding size, load, timing, etc. are available. Also the designation of the instrument is lacking. It was named "Minsk" by this writer for the purpose of a record only.

The "Minsk" penetrometer, in spite of lack of the detail of its construction and use, is significant from the important viewpoint: it served the vehicle designer who was primarily interested in the "effect of dimensions of track bearing areas upon traction, and vehicle mobility." in given soil properties (Matsepuro and Hao-Sin-Fan, 1962).

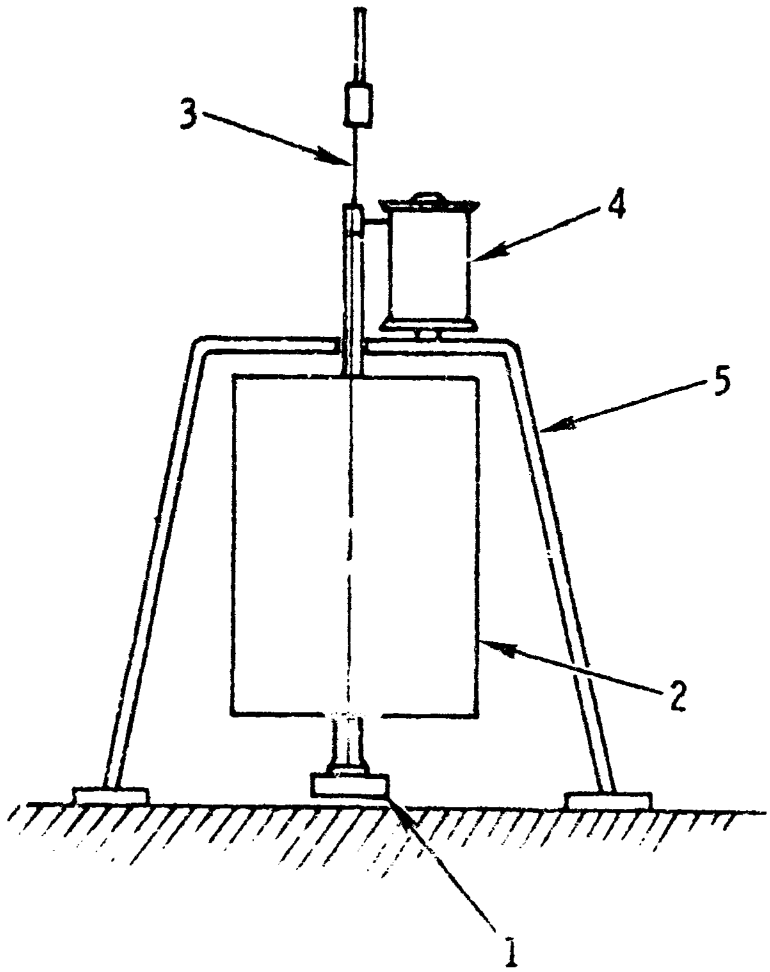


Figure 19 "Minsk" Penetrometer (Matscpuro and Hao-Sin-Fan (1962))

The need for soil measurements which could be used in such a parametric analysis of design was already clearly in sight, as will be shown by the development of instrumentation described for the period of 1960 to 1966. The "Minsk" device is an early augur of a new trend.

Revolt of Vehicle Designer: Search for New Instrumentation

As mentioned before, the Russian soil values were largely dependent on the form and size of measuring apparatus. For this reason their use in mathematical modelling of soil-vehicle relationship and vehicle development was limited. The empirical "indices" could serve no designer.

However, the publication in America of new theories (Bekker, 1956, 1960), which reverberated in Russia not without an echo, seem to have encouraged the designer of tractors and other vehicles to seek his own instrumentation.

From the time of Letoshnev (1936) it was known that an absolutely error-free soil testing apparatus should utilize the form-size-load configuration of the probe, identical to that of the ground contact area of the vehicle under consideration.* However, the field and laboratory instruments were not built for that purpose until after 1956. They originated at NATI and NAMI, i.e., at the automotive, and the machine design research institutes (Guskov, 1966). From there they were adapted by agricultural engineers of the Central Scientific Research Institute for Mechanization and Electrification of Agriculture (TsNIMESH). This development represents a revolt of the designer against all the "indices" with which he had been supplied since the beginning of this century, and which as Grinchenko et al. (1967) pointed out can "never lead to an improved design." It is characteristic that this trend was not started by theoreticians, on the basis of a "new" soil mechanics, but by the automotive test engineers who decided to replicate their tracks and wheels in test rigs rather than to resort to already confusing correlations between "indices" and vehicles.

The full size model-equipment evaluation has always been the trademark of automotive engineering since Becker (1926) made the first tests of agricultural tractors in Berlin,

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* This has been the basis of the bevameter technique (Bekker, 1960, 1969).

and one may wonder why it was revived so late. The explanation, however, appears to be simple. Development and production of a mechanically reliable piece of machinery demands 50 times more time and money than the study of soil-vehicle relationship. Moreover, reliability has always come before what is called "mobility." Thus, there were practically no people in the automotive profession interested in soil. As a result the solution of the multiplicity of problems of terrain-vehicle interface, which only recently came to light, were left to agricultural, civil, or military engineers.

Since this did not give the Russian designer tools for the development of more "mobility," he rebelled.

Field Wheel Testing Instrument TsNIMESH (1960 to 1966)

The rebellion grew with the design and development of better vehicles becoming more involved, and with the existing soil testing equipment becoming more outmoded and controversial. The Russian engineers soon began to realize that wheels of agricultural machines were often "adopted without sufficient justification" (Kuzmenko, 1960) and undoubtedly remembered that Letoshnev (1936) tested a full size wheel on carriages under field conditions; as a result they resorted to the construction of a special field test dynamometer in Letoshnev's fashion. However the instruments they designed were to record the drawbar pull, slip, sinkage, motion resistance, etc. of a single wheel rather than of a combination of wheels. This method was selected in order to obtain a better picture of wheel performance than the picture obtained in the study of a complete vehicle.

It should be noted parenthetically that identical, more sophisticated test equipment already existed in the U. S. for use in soil bins. But a comparable American single-wheel field test apparatus remains unknown to this writer, except for tire testing on the highways and certain tests at USDA in Auburn, Ala.

A sizeable number of field test instruments for optimization of tire-soil system was built in the U. S. S. R. after 1956. Guskov (1966) reviewed progress made in Russia and abroad, referring to the prototype of such an instrumentation as originally developed by NIAE in England (Bailey, 1954). Similar instrumentation developed between 1952 and 1957 in East and West Germany also was mentioned.

The Russian development started in 1956 at NATI and NAMI. It was pursued by automotive and mechanical engineers. This instrumentation, adopted by agricultural engineers, was first described as far as could be ascertained by Kuzmenko (1960) and later by Guskov (1966).

Kuzmenko's tire tester is shown in Figure 20.* According to the brief description by Guskov, the instrument was towed to the test place on sleds (7). Wheel-carrying frame 5 could be placed at any height in accordance with wheel dimensions. The test load was provided with weight 6, recorded by dynamometer 4. Tension rollers 3 for chain drive of the tire enabled the power transfer, irrespective of wheel sinkage, driving, or braking. Longitudinal and vertical movements and loads of the wheel were electrically recorded by gauges 1 and 2, and an eight-channel recorder, MPO-2. Towed, braked, and driven wheels could be tested up to 600 mm width and 600 to 2000 mm diameter. Power was provided by an automobile engine, GAZ-MM. Wheel load could vary from zero to 3000 kg; test speed could change up to 15 km/h. Tire deflection and sinkage were measured with electric gauges. In order to reduce the effect of sled load upon tire performance, the skis were spaced at 1.25 m distance from the wheel, and their load did not surpass 0.1 kg/cm^2 ground pressure.

The trend to resort to full size testing rather than other indirect methods apparently gained momentum with the development of pneumatic tires. It led to successful work on tire theory by Ageikin (1959, 1960), for instance, and to a rational collecting of test data needed for both practical and theoretical evaluation of soil-vehicle performance (Armaderov et al., 1962; Armaderov, 1964, 1965).

This movement was spreading in a parallel direction of track studies, and soon led to the development of modern instrumentation of land locomotion laboratories and proving grounds.

Track Testing Instrument DSSH (1960 to 1966)

The first theory of land locomotion (Bekker, 1950, 1956) was already published in the U.S. when the description of the track-testing instrument appeared in the prestigious

* The "nineth wheel" and the instrumented wheels of the Russian Rover "Lunokhod" undoubtedly collected data for wheel and vehicle designer, in much the same manner as Kuzmenko's device.

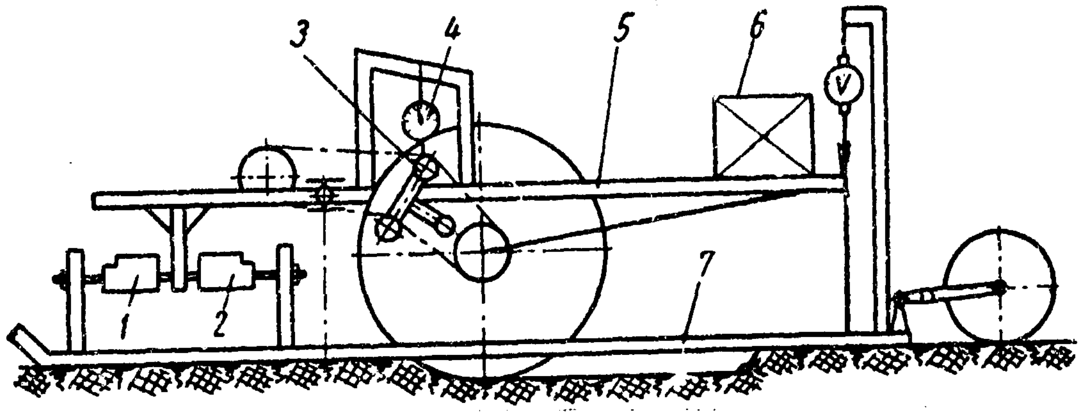


Figure 20 Tire Test Rig for Field Use. Kuzmenko (1960)

'Voprosy. . . " (B.V. Zapolski, 1960). The instrument was an improved, sophisticated replica of the first prototype of its kind conceived in Canada and described in the United States (Bekker, 1950). The general view of the Russian machine is shown in Figure 21. Vertical hydraulic cylinder 1 equipped with pressure control 2 and 3 was mounted on carriage 4, which could move on guide frame 13. Cylinder 5 operated anchor 6 which kept the test rig in place during the experimentation. Hydraulic cylinder 7 moved horizontally carriage 4 with the test track 8 when the track was loaded vertically with cylinder 1. The chassis had its own power source 9. Oil tank 10 fed horizontal cylinder 7 through pump 14. Controls 11 adjusted the pressure. Speed control 12 provided constant deformation strain of the soil sheared by the track under test.

The most interesting part of the instrument was the "floating mount" of the tested track, Figure 22. A portion of rod 1, which provided vertical track load, was shown pressing against frame 4. In the frame, the middle track link 3 was mounted by means of a suspension in such a manner that it transferred the horizontal and vertical loads to the electric cells 2, and to the recorder. Two other identical track links were mounted rigidly on frame 4. In this way the first and the third track links moved together with the middle link under identical loads, and created the same soil load conditions for the dynamometric link 3 as those existing under a link of the real track. The "bulldozing" effect of the measured track part, which in this type of test used to spoil the accuracy of the experiment, was thus completely eliminated. An identical "floating" link, preceded and followed by two rigid links assemblies was conceived, built, and used independently, by General Motors Terrain-Vehicle System Laboratory in Santa Barbara, from 1963 to 1965.

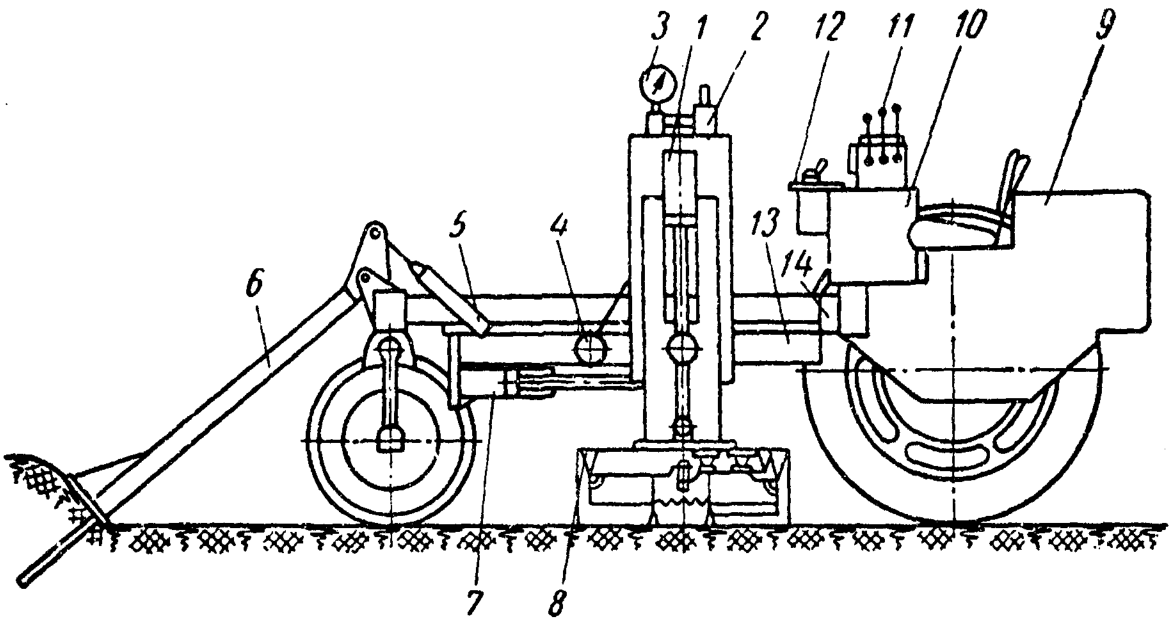


Figure 21 Track Testing Instrument on DSSH Chassis (1960)

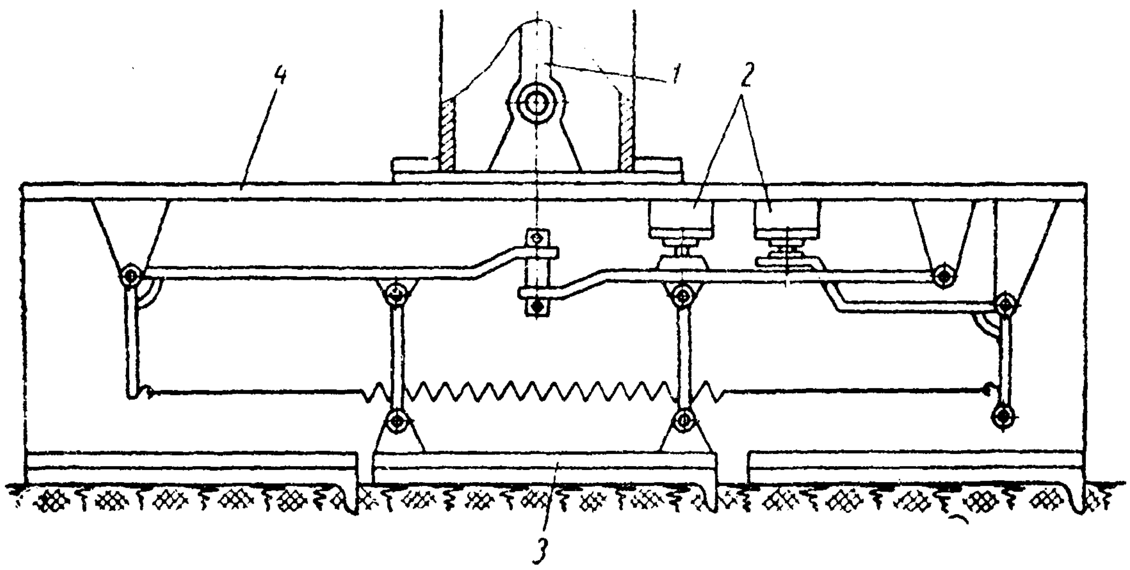


Figure 22 "Floating" Mount of the Track under Test (Zapolski, 1960)

The sophistication of the Russian instrument, however, went further: in order to simulate the dynamics of track link - soil interaction, pulsating hydraulic systems were used with a programmed frequency and amplitude of horizontal movement. Vertical load changes also were programmed into the movement of the carriage along the guide rails.

The studies of track pull, slip, and sinkage under the given loads were performed for horizontal speeds of the carriage from 0.02 to 1.2 m/sec. The ground pressure acting upon the tested track could be changed from 0 01 to 1.5 kg/cm^2.

The instrument appears to have become standard equipment, since its description together with Figures 20, 21, and 22, was again produced in Guskov's (1966) book on optimization of tractor parameters.

Wislicki (1969), in Poland, also developed instrumentation similar to the DSSh apparatus. His device, however, was designed for laboratory use in a soil bin, and the shear measuring plate was a rigid, single-unit track portion. The measurements encompassed k_c, k_φ, c, and φ. It was in a true sense, a bevameter.

In the context of available literature it became evident that the DSSh track-testing instrument served the purpose of defining soil values in shear (c and φ) as well as Katsygin-Guskov parameters k_{KA} and p_{KA}, which were used in optimization of vehicle design and performance, within the same size-load envelope.

Guskov admitted to this writer that the limitation of soil measurements which required instrumentation of very large size was a serious handicap. Since the early advent of a Russian generalized soil value system seems, however, most probable, as discussed in Chapter II, further development of instrumentation of the DSSh kind appears certain.

Turf Penetrometer DT-55 (1966)

Perhaps, the development of a soil measuring device applicable to all practical size-load envelopes has already started; this device may be the field penetrometer developed by the TsNIMESH. It did incorporate the load-penetration measuring instrument, which like the bevameter previously developed by the Land Locomotion Laboratory, recorded the load-sinkage curves for the purpose of fitting them with a mathematical function containing soil values. Naturally, the Russian engineers used Katsygin's hyperbolic function, as described in Chapter II (equation (24) and Table 8):

$$p = p_{KA} \tanh \left[\frac{k_{KA}}{p_{KA}} \right] z$$

and determined in the field test values of p_{KA} and k_{KA}. In order to cope with the effect of plate size in turf they used the Housel formula (1929) (equation 18):

$$p'_{KA} = A_o + B_o \frac{U}{A}$$

The sophistication of the method, however, surpassed here the bevameter technique because, in turf, the speed effect upon p_{KA} and k_{KA} was significant and must have been considered. The relationship between p_{KA} and k_{KA}, and the speed v was assumed in accordance with equation (59):

$$p_{KA} = p'_{KA} + c_v v^2$$

$$k_{KA} = k' + mv^2$$

Coefficients c_v and m were determined by a series of experiments at various v's by means of the least square method. Thus the final Katsygin's equation used for fitting the load-penetration curve obtained with this penetrometer had the following form:

$$p = (p'_{KA} + c_v v^2) \tanh \left[\frac{k_{KA} + mv^2}{p'_{KA} + c_v v^2} \right] z \tag{82}$$

where the extrapolation for contact areas other than those used in the penetrometer was performed on the basis of equation (18). The field penetrometer built on DT-55 chassis, Figure 23a, thus represented a copy of the field bevameter (compare Figure 1-2 in reference Bekker, 1970, Part I); only, the "Russian equations" were fitted into the empirical curves instead of "American equations."

The DT-55 instrument for soil measurements as shown in Figure 23a (Melnikov, 1966) was mounted on tractor 1 by means of frame 2 equipped with stabilizing support 3. Penetrometer plate 4 was actuated by a complex hydraulic system 5 which controlled not only the load but also the speed of penetration plate 4. The speed could vary between zero and 0.38 m/sec. It was contemplated to increase the speed up to 4 m/sec.

Penetrometer plates were round or square with areas varying between 12 and 110 cm^2. This set of plates was found useful for very soft-turf ground with 90% moisture content. p_{KA} was then usually found to be equal to 1.58 to 1.62 gr/cm^2.

Figure 23b shows the effect of speed of penetration upon the bearing strength p of turf. The experimentally determined soil values p_{KA} and k_{KA} are shown in Figures 23c and d as a function of penetration speed v.

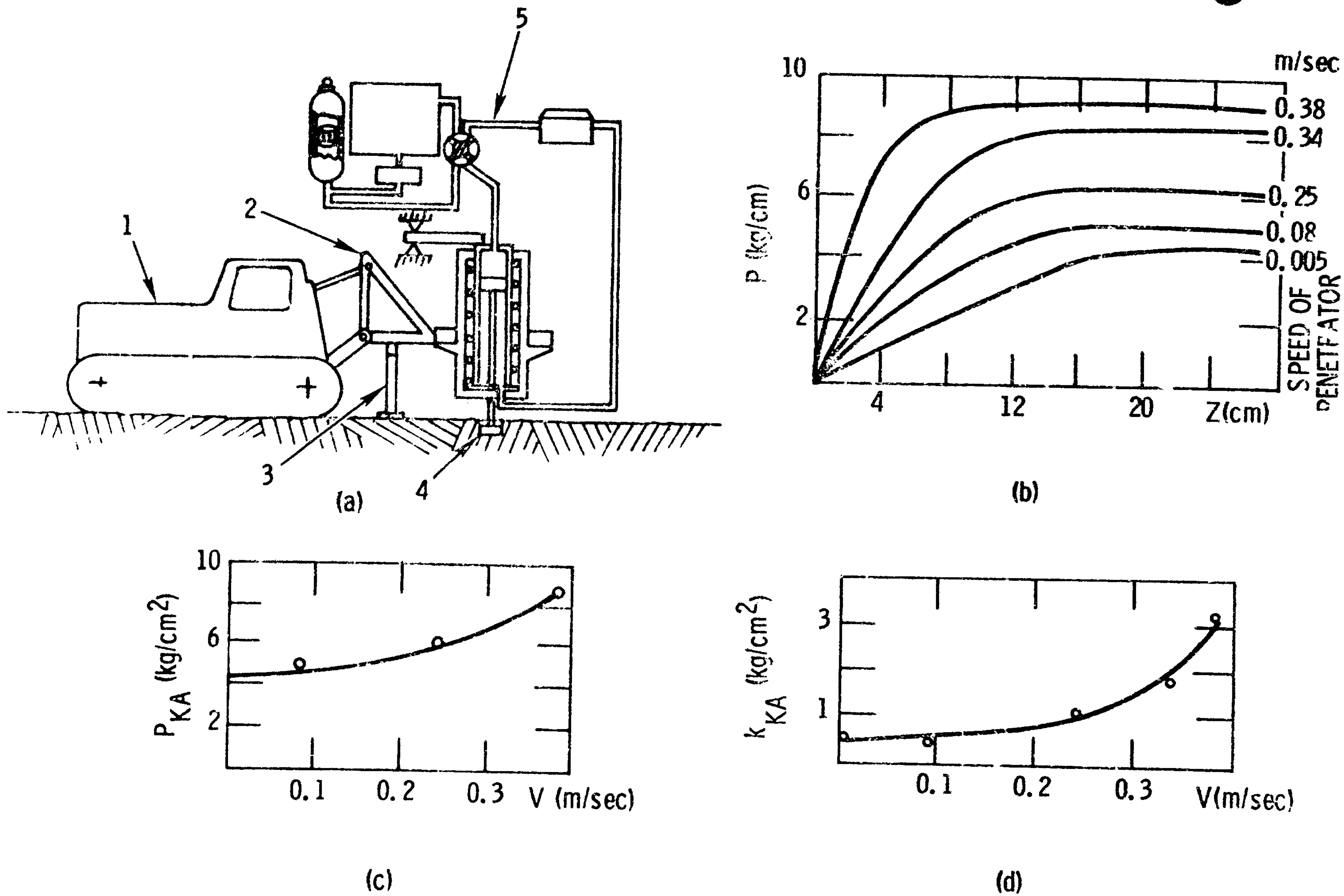


Figure 23 Soil Measuring Device with DT-55 Tractor (Melnikov, 1966)

This Russian development of modern field and laboratory instrumentation, which has been narrowing the gap between their and the American approach, is perhaps well characterized by an excerpt from a letter to this writer by Professor Guskov (1969):

> "I have been reading (your book on Introduction to Terrain-Vehicle Systems)... with my intense desire to translate this book from English into Russian." *

Vehicle User and Rokas' Penetrometer (1969)

Two students of vehicle mobility and ground trafficability, Poliakov and Nafikov (1969), revived the idea of Rokas' penetrometer (1960). Although, as mentioned before, they never referred to Rokas, they used not only his instrumentation for soil measurements (Figure 8) but also the basic ideas, with a mixture of concepts by Ageikin and Letoshnev-Bekker.

Poliakov-Nafikov's main attempt was to replace the empirical correlation between the arbitrary indices obtained by Rokas instrumentation and vehicle performance, with formulae based on previously established concepts of soil-vehicle relationship (Bekker, 1956; Ageikin, 1959). Thus, for instance, the adhesion of the wheel μ_a was defined in terms of Coulcmb's law"

$$\mu_a = \frac{c}{p} + \tan \varphi$$

where c was soil cohesion and φ-friction; p was tire ground pressure. Since Rokas' (1960) soil values $\Psi_1(\tau)$ and $\Psi_2(p)$ were too crude, Poliakov and Nafikov (1969), using Rokas' penetrometer, expressed μ_a by an equation which included the (unspecified) dimensions of the cone-cum-blades device, in the following form:

$$\mu_a = \frac{2\,TF}{\pi d^2\,[d/6) + h\,]\;W} + \frac{2\,(p_{av} - 10\,c)}{p_{av} + 40\,c} - 0.05 \qquad (83)$$

where T was penetrometer torque (kg cm); F was ground contact area of the tire with the ground; d was the diameter of vane circumference; p_{av} was the average

* The "Introduction to Terrain-Vehicle Systems" is scheduled to appear in Russian translation in 1972.

"pressure" (calculated on cone base) of two penetration tests: one to the depth of vanes z_1 and the other z_2 deeper than z_1 (Figure 24a); and cohesion calculated from the shear vane test.

The formula for wheel gross pull was based on another equation for "optimum ground pressure" p_m, based on work by Ageikin (1959) and on unspecified "calculations which showed that the best agreement with experiment is given by equation:"

$$p_m = \frac{W}{F} = \frac{W}{0.5\,\pi(D/2)\,\Delta\sqrt{\left(2-\frac{\Delta}{D/2}\right)\left(\frac{b-\Delta}{D/2}\right)}} \tag{84}$$

where D was tire diameter and Δ was its deflection; b was tire width assumed as the height of its profile; and 0.5 was an empirical coefficient. With the help of this equation, Poliakov and Nafikov proposed a formula for tire motion resistance in the following form:

$$f = \frac{P}{W} = \frac{2\sqrt{z\,(b-z)}}{K_{NP}\,W}\,(p_m - k'_{NP}z) \tag{85}$$

where k_{NP} and k'_{NP} are Nafikov-Poliakov soil values explained in Chapter II; z was tire sinkage.

Using Rokas' penetrometer twice, and recording "cone pressures" p_1 and p_2 at two sinkages z_1 and z_2, values of K_{NP}, k'_{NP} and z were determined from equations:

$$\left.\begin{aligned}
K_{NP} &= \frac{z(z_1p_2 = z_2p_1)}{z_1p_2\,(z_2 - z_1)}\\
k'_{NP} &= \frac{p_1}{z_1}\,(1 + K_{NP})^3\sqrt{\frac{F}{A}}\\
z &= \frac{1}{K_{NP}}\,\ln\left[\frac{p_m K_{NP}}{k'_{NP}} + 1\right]
\end{aligned}\right\} \tag{86}$$

The method was tried for various wheeled vehicles and various types of soils. Thus, calculated values of μ_a and f were analyzed statistically in order to determine their level of confidence (Table 18).

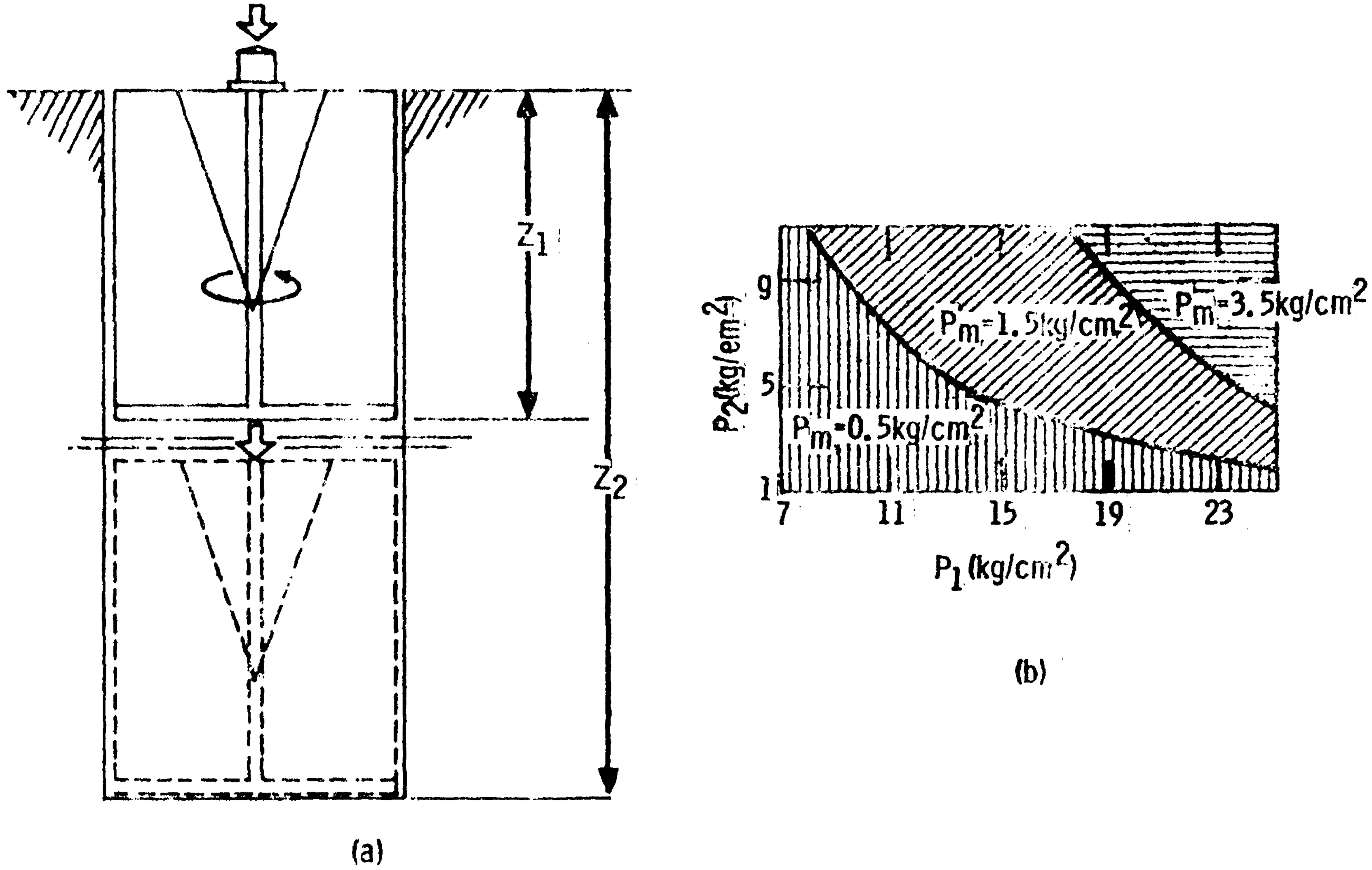


Figure 24 (a) Rokas-Nafikov-Polikov (1969) cone-cum-vanes penetrometer, (b) penetrometer "pressures" p_1 and p_2 versus optimum inflation pressure of a tire for ZIL truck

Table 18

		Standard Deviation	Coefficient of Variation %	Confidence Level p=0.01	Confidence Level p=0.05
μ_a		0.040	52	0.20	0.79
normal infl. press		0.001	137	1.00	1.00
f for:	infl. press. 1-2 kg/cm^2	0.022	71	0.35	0.98
	infl. press. 0.5-1 kg/cm^2	0.019	83	0.40	0.99

The author's comment on Table 18 is as follows: "confidence in determining (with Rokas' penetrometer and Nafikov-Poliakov equations) values of μ_a and f for 5% significance level may be considered acceptable." It is suggested that the reader draw his own conclusions as to the use of Rokas' instrument for the considered purpose.

Calculations performed for a truck, ZIL-157, at various inflation pressures produced graph Figure 24b, which maps zones of optimum inflation defined by penetrometer indices p_1 and p_2 and the corresponding K_{NP} k'_{NP} values. To what extent all these data were correlated with dynamometric tests of actual vehicles, in the soils defined by the Rokas-Poliakov-Nafikov penetrometer method, remains unknown.

The cone-cum-vanes penetrometer of Rokas (1960) espoused by Poliakov and Nafikov (1969) was a hand-operated gadget weighing 3 to 5 kg., or a mechanically operated instrument weighing 300 to 500 kg.

The operational procedure for reconnaissance required three steps: the tip was forced into the ground to the depth equal to the height of the vanes. At that time, cone "pressure" p_1 was read on the dial. Next, the penetrometer was rotated and torque was read. The third step was to force the penetrometer to a larger depth and to read pressure p_2. From there, the previously described calculations were hopefully aided with a series of alignment charts computed in advance, for vehicles under stuty. Their trafficability in terms of inflation pressure, for instance, was thus established. In addition, the calculation of μ_a and f enabled one to estimate negotiable slopes, payload, and axle loads.

Another article by Poliakov-Nafikov (1968 a) does not show any correlations between calculations and actual measurements. Therefore the accuracy or practicability of the method could not be ascertained.

The use of Rokas' penetrometer by Poliakov-Nafikov, even for a limited design purpose, also is unknown. It was superceded between 1960 and 1966 by the more rational instrumentation and methodology required in automotive engineering. This methodology produces mathematical models of soil-vehicle relationship based on practical Katsygin-Matsepuro-Guskov techniques. Thus from the viewpoint of design and development of motor vehicles, the present writer is inclined to dismiss Poliakov-Nafikov's (1964) work as another fine but anachromistic exercise by non-automotive researchers.

Their work did not produce an echo among the designers, for it represented the ultimate requirements by vehicle users who normally and understandably want too much for too little. In addition, user requirements often reflect the conceptual "status quo," only disguised in an appearance of novelty which has little to do with progress.

The requirement for a quick, accurate measuring "in situ" of soil trafficability, usually on "go - no go" basis, has survived the trials of half a century because of the historical bias of the user, although the practicability and the real need for such a requirement may be questioned on various grounds. One reason for questioning the need for a gadget which predicts "mobility" in terms of a "go - no go" yardstick, may be based on the fact that after some 30 years of a massive effort (Waterways Experiment Station) no equipment for that purpose has ever been adopted on a meaningful scale by any civilian or military organization, either in the U. S. S. R., this country, or abroad, as far as it could be ascertained.

Although a discussion of this problem is beyond the scope of the present analysis, the question has been raised again in order to assess the extent to which Nafikov-Poliakov represented the true or imaginary requirements. The answer appears clear when they published their second paper with the preamble:

> "special difficulties are caused by the crossing of swamps... clay soils and loose sands by wheeled vehicles... Therefore it is more often advantageous... to reconnoiter (the terrain). Terrain trafficability reconnaissance is a difficult task. Until now vehicle mobility in adverse terrain was determined by tests in situ, which are expensive and not always possible. However, now a special penetrometer has been developed for this purpose" (Poliakov-Nafikov, 1969 a).

This sounds like a quote from World War II U. S. Army requirements, which have reverberated ever since, in some circles.

What school of thought was prevailing in 1969, and what was the motivation of Poliakov and Nafikov to resurrect this 30-year-old requirement and to take the 1960 instrument by Rokas which was a hybrid of 1943 to 1947 ideas by American WES and British AORG, remains a matter of conjecture. Whether there was a problem or not, the user started all over again.

Did this represent a true requirement of the Russian engineers? Considering the discussed background the answer appears negative. And in addition, if there was a requirement it would have been published much earlier.

Lunar Soil Penetrometer "Lunokhod"

The latest development in instrumentation of soil measurements is the Lunar soil testing device operating on the moon with the "Lunokhod" vehicle.

> "One (instrument) consists of a flat surface at the end of a rod to be stamped into the lunar material during stops ... The other is the ninth wheel (which) is lightly loaded (and) does not slip as the heavily loaded drive wheels" (Aviation Week & Space Technology, 1971).

If this is correct, the instrumentation is a replica of the standard flat plate penetrometer and of the TsNIMESH wheel test apparatus (Figure 20). The interpretation of soil-values in all probability will be performed in accordance with the methods discussed in this report. An article by "Pravda" dated 9 February 1971 states that the penetrometer is like a needle, and implies that it tests lunar soil stratification.*

From the User to the Designer

The rationalization of Russian modelling of the soil-vehicle interface was a slow, evolutionary process, as seen in the chronology of development of instrumentation. The rationalization aimed at enabling the automotive engineers to design better vehicles rather than the user to set operational schedules. Nevertheless the user did benefit, in the long range, from such an approach, for the need for hasty "in situ" soil checks had been diminishing, thanks to increasing vehicle performance.

* Information received at the time of printing this report indicates that the instrument is a cone-cum-vanes penetrometer. It was designed by geologists and soil scientists.

The user's independence as a client, however, has always induced him to foster new requirements. Since most of the ideas have already been explored during the period of more than 60 years, the same concepts appeared over and over again, in different mantles. This is why, among others, the antiquated ideas of soil-measuring instrumentation survived decades. The lack of professional heritage, coordination, and interchange of thought were as much a stumbling block in Russia as they are in the West.

But the rational treatment of the problem became unavoidable. Progress started by Russian automotive engineers was finally adopted by the students of agriculture tractor design. It encompassed the field testing of soil by often using one-to-one instrument replica of the critical vehicle element.

The clumsiness and limitations (as well as the advantages) of such an approach were recognized, and a search for generalized soil values for systems analysis was undoubtedly inaugurated (Chapter II). Whatever the outcome may be, the penetration and shear instruments as represented by DT-55 and DSSh will stay. Their basic concept will not change, though their size and weight may; for there has been no other method invented to probe the soil.

It is apparent that the Russian soil-measuring instrumentation had, in principle, approached the American bevameter type instrumentation. The gap that existed in the early fifties does not exist any more. Russian, like American soil measuring hardware, suits the designer rather than the user. But there is no reason why it should not be adapted more explicitly to "field reconnaissance" if World War I and II requirements still really exist. Do they?

CHAPTER V
MATHEMATICAL MODELLING OF SOIL-VEHICLE INTERFACE

Introduction

Mathematical modelling of wheel-soil interface was started by Bernstein (1913), and expanded with experimental verification by Letoshnev (1963).

Their work laid the foundation for further development of quantitative analysis of soil-vehicle interface, based on physical and geometrical terrain and vehicle values. Since the above attempts of establishing locomotion mechanics were described in detail (Bekker, 1956), and since they were briefly recounted in Chapter II, the present discussion will start with post-Letoshnev developments.

Historical review of Russian work on locomotion mechanics does not show the variety of sophistication of approaches that exists in the West. For this reason the solution of the problem became more simple. On the other hand, the unsophisticated Russian approaches raised the question of quality, and cost of solutions obtained in comparison with similar American and other achievements. Accordingly, the foregoing lines will represent a comparative analysis of Russian and other modellings of soil-vehicle interface, rather than a mere historical review of Russian mathematics and geometry of locomotion.

The main theme of this Chapter will be to define the tradeoffs between sophistication (cost) of the method and the accuracy of prediction (effectiveness). Attempts at forecasting future developments also will be made.

Rigid Wheel

Extensive studies by Letoshnev (1936) established permissible loads on horse-driven carriages, in various soil conditions. This was done by considering the draft of the carriage in terms of wheel dimensions, axle load distribution, wheel sinkage, and Bernsteinian soil values k and n.

Early developers of tractors (on rigid wheels) did not pay proper attention to Letoshnev's work although it represented the only theory available. There was no concerted

expansion and refinement of the theory and soil value system. Instead individual researchers attacked the problems of their choice. Thus, Vernikov (1940) of the Ukrainian Institute for Mechanization of Agriculture was critical that the theory did not consider speed of soil deformation, which was all right, as he implied, for horse-driven carts, but not good for the speedier tractors. Hence he attacked perhaps the least urgent aspect of the problem, instead of concentrating on the more serious deficiencies of the Bernstein-Letoshnev theory such as limitation of soil values, over-simplifying assumptions, etc.

This he did with imagination. If a plate sinkage to depth z compresses soil with speed v, then the time of compression is $t = z/V$. Soil particles adjacent to the plate move with the plate, and those located in a layer below the plate move slower, depending on the depth of the layer. Assuming that this "slow down" of sinkage is controlled by coefficient u, Vernikov calculated the "total" vertical movement L of soil layers, or the "depth of compaction," as he put it, of compressed layers as follows:

$$L = \sum_{1}^{n-1} vt = vt + vut + vu^2t + \ldots vu^{n-1}t$$

and,

$$L = \frac{vt}{1-u} - \frac{vu^n t}{1-u} = \frac{z}{1-u} - \frac{zu^n}{1-u} \ldots\ldots \qquad (87)$$

Since $u < 1$, the "depth of compression" of soil for $u \to 0$, is:

$$L = \frac{z}{1-u} \qquad (88)$$

From this Vernikov deduced the "average speed" of compaction

$$v_{av} = \frac{L}{t} = \frac{z}{(1-u)t} \qquad (89)$$

and the "average acceleration":

$$a_{av} = \frac{v_{av}}{t} = \frac{z}{(1-u)t^2} \qquad (90)$$

the value of u, according to Vernikov, can be determined experimentally from the densities γ and γ' of soil before and after compaction:

$$u = \frac{\gamma}{\gamma'} \qquad (91)$$

Thus the dynamic resistance P_d of soil compression caused by inertia forces is

$$P_d = \int_0^z a dm \tag{92}$$

where a is acceleration of elementary soil mass dm. If the compacting area is F, then he assumed that:

$$dm = \frac{F\gamma dz}{g} \tag{93}$$

and from equations (90) (92) (93):

$$P_d = \frac{F\gamma z^2}{2(1-u)gt^2} \tag{94}$$

Taking as the point of departure, Bernstein-Letoshnev criterion $p = kz^{\overline{n=1}}$, vertical load was determined from the formula:

$$P = Fk_v z \tag{95}$$

Next, Vernikov equated formulae (94) and (95). Thus soil parameter k became Vernikov's "dynamic" sinkage parameter k_v:

$$k_v = \frac{\gamma}{2(1-u)gt^2} \tag{96}$$

Vernikov also assumed that for small values of z:

$$z = \frac{gt^2}{2}$$

hence:

$$k_v = \frac{\gamma gt^2}{2(1-u)gt^2} \tag{97}$$

and for $u = \gamma/\gamma'$, equation (91):

$$k_v = \frac{\gamma\gamma'}{2(\gamma'\gamma)}$$

as it was reported in Chapter II, equation (15). The depth of sinkage was determined from equation (94) as follows:

$$z = \sqrt{\frac{2P_d(1-u)gt^2}{F\gamma}}$$

and in combination with equation (97),

$$z = \sqrt{\frac{Pgt^2}{Fk_v}} \tag{98}$$

Assume that the ground contact area F of the rigid wheel of diameter D equals the length of the chord $\sqrt{z\,(D-z)}$ at sinkage z, times width b:

$$F = b\,\sqrt{z\,(D-z)}$$

For very small sinkage z, the contact area is:

$$F = b\,\sqrt{Dz} \tag{99}$$

Substituting force P with wheel load W and combining equations (99) and (98), the dynamic sinkage z of the wheel was expressed by formula:

$$z = \sqrt[5]{\frac{W^2 g^2 t^4}{k_v^2\, b^2 D}} \tag{100}$$

Vernikov stopped on equation (100) and discussed at length what will happen if the speed of compression of soil by the wheel is greater or smaller than the speed of "free fall." He further assumed that if the wheel chord length is $\sqrt{Dz}$, equation (99), and the rolling speed is v, then the average time of wheel action upon soil is:

$$t = \frac{\sqrt{Dz}}{2v} \tag{101}$$

The "free fall" time-sinkage equation is:

$$z = \frac{gt^2_{ff}}{2} \tag{102}$$

and the time is:

$$t_{ff} = \sqrt{\frac{2z}{g}} \tag{103}$$

If wheel speed v is such that soil compression time t, equation (101), is smaller than time t_{ff} in which sinkage z would occur in "free fall" of the load, equation (103), then any speed increase reduces sinkage. For the reverse condition the sinkage increases in accordance with equation (100).

The critical speed v, above which sinkage is reduced, is thus defined by equations (101) and (103) from inequity $t_{ff} > t$, or

$$\sqrt{\frac{2z}{g}} > \frac{\sqrt{DZ}}{2v}$$

or, approximately:

$$\frac{D}{4v^2} \angle 0.2 \qquad (104)$$

This was the main conclusion of Vernikov's paper. In order to present equation (100) in a tangible form, this writer combined it with equations (101) and (15). Accordingly, sinkage for the condition expressed by equation (104) was

$$z = 3\sqrt{\left[\frac{Wg}{2v^2}\frac{(\gamma' - \gamma)}{b\gamma'\gamma}\right]^2 D} \qquad (105)$$

Note that the effect of changes in soil density γ "before and after" wheel rolling was not experimentally defined or verified.

Formula (105) was to improve the simple Bernstein-Letoshnev equation (106) based on $p = kz^n$ for $n = 1$ (see Bekker, 1956):

$$z = 3\sqrt{\frac{9W^2}{4b^2k^2D}} \qquad (106)$$

The reader is invited to count the number of new assumptions added to equation (106) by Vernikov, starting with unproven equation (87). It is certain that "speed correction" introduced in this fashion could only deteriorate the Bernsteinian accuracy of prediction of wheel sinkage, and obscure the outcome of experiments.

Equations (100) or (105) were never verified experimentally, as far as it could be ascertained. Data quoted by Vernikov from tests made with a 5 T-3 NATI tractor were completely unreliable. The process of soil definition by measuring pre- and after-compression densities is complex, if practical at all. In addition, the measurement must be performed with an instrument replicating the full load-size form of the wheel. Then, in the best case, the argument of performance prediction becomes circular.

Vernikov's work showed a lack of general research strategy, a lack of priority system in planning, and a lack of reporting the complete work. Yet it was intriguing, and to a degree educational, in the bold manipulation of parameters involved and in the unsophisticated engineering rather than scientific methodology.

Expensive, sophisticated Canadian-American work using x-rays and computerized instrumentation, which was repeated much later (Yong, 1969), was no more successful, for practical purposes, than Vernikov's (1940) paper study. It proved, however, that simpler, approximative approaches by the Russians are the less costly, and often prove to be a useful educational exercise in the preparatory planning of engineering research.

Kragelski (1948), a contemporary of Vernikov, was preoccupied with snow compaction. But he was not concerned with the speed of compacting rollers, and adopted without restriction Bernstein-Letoshnev criterion of $p = kz^{n=1}$ (actually quoting Grandvoinet's 1967 work, which was apparently one of the first to define p(z) curve). He even measured k with a disc having 6 cm^2 area, and used for definition of motion resistance of the rigid roller in snow, the equation:

$$R = 3.42 \sqrt[3]{\frac{W^4}{bkD^2}} \tag{107}$$

which is identical, except for coefficient 3.42, with Bernstein-Letoshnev's equation for soil (Bekker, 1956):

$$R = 0.\text{[illegible]} \sqrt[3]{\frac{W^4}{bkd^2}} \tag{108}$$

Automotive engineers contemporary to Vernikov and Kragelski followed suit. A comprehensive book on design of automobiles, trucks, and tractors for on- and off-road locomotion (Martens, Ed., 1948) espoused among others, Bernstein-Letoshnev's equations for wheel sinkage in the form,

$$z = \sqrt[3]{\frac{2.25\, W^2}{b^2 k^2 D}} \tag{109}$$

which was identical with equation (106) for n = 1. The common use of n = 1 by these authors, although improper for the majority of soft soils, may be explained by the fact that the pertinent formulae give very good correlations between experiment and theory,

because of $n = 1$ the soils are hard, and the sinkage is low. Martens' contributors also used equation (108) in order to express rolling wheel resistance.

This indicates that automobile designers did not conduct at this stage, any independent work, and relied on agricultural engineers for research purposes.

Gutyar (1955), writing for an agricultural engineering magazine, also tried like Vernikov, to improve Bernstein-Letoshnev's equations (which he called Grandvoinet-Goryachkin). However he was not concerned with the correction for speed of wheel travel. Instead he thought the equations could be improved if soil were considered as a compound, elasto-plastic material, and not as a "plastic" mass having only one modulus of inelastic deformation k_B or k_L, based on $p = kz$.

He recalled that even Academician Zheligovski (1937) and Professor Vasilenko (1950) relied on the Gradvoinet-Goryachkin (Bernstein-Letoshnev) equation, although it does not recognize the partial elastic rebound of soil after the passage of the wheel, which all of them noticed a long time ago.

Gutyar's approach, like Vernikov's, was simplistic. Assume that wheel sinkage z_1 is partially recovered due to elastic rebound of soil so that the depth of the rut is z_2 (Figure 25). Denote by k_G the "elasto-plastic" modulus of soil deformation in front of the wheel, and by k_G^1 the "plastic" part of the modulus which produces permanent sinkage z_2; then, at point A, the unit load p is, according to Gutyar:

$$p = k_G z_1 = k_G^1 (z_1 - z_2) \tag{110}$$

and at an intermediate point B on either front or rear side of the wheel:

$$p_1 = k_G (D/2)(\cos\alpha - \cos\alpha_1) \tag{111}$$

$$p_2 = k_G^1 (D/2)(\cos\alpha - \cos\alpha_2) \tag{112}$$

Thus, wheel load W was expressed by Bernstein integrals:

$$W = \frac{bD}{2}\left[\int_0^{\alpha_1} p_1 \cos\alpha \, d\alpha + \int_0^{\alpha_2} p_2 \cos\alpha \, d\alpha\right] \tag{113}$$

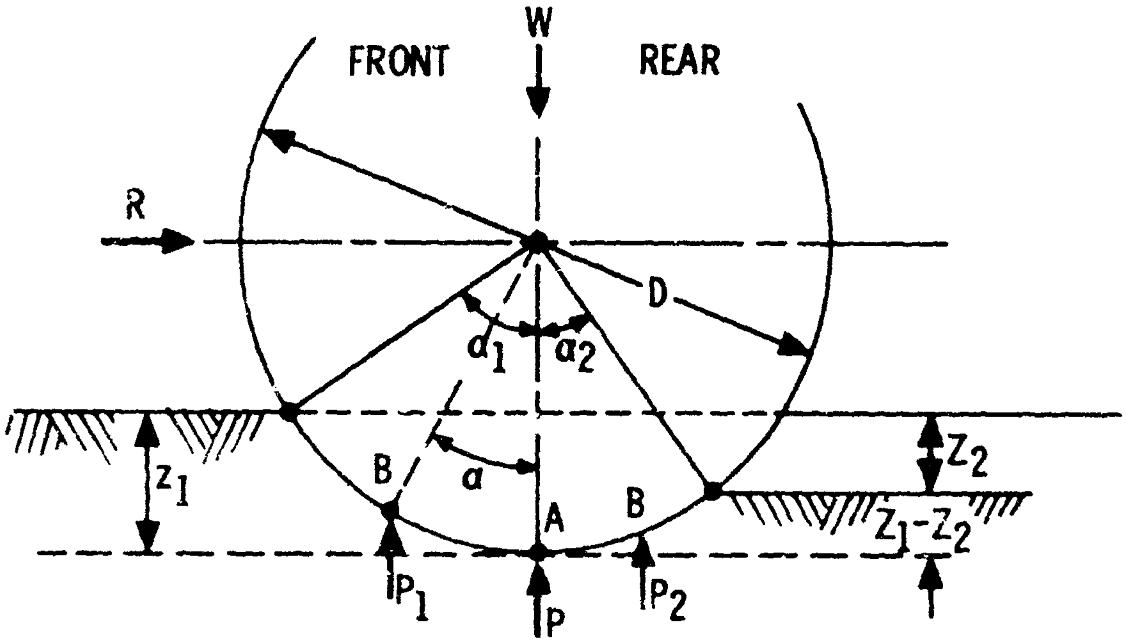


Figure 25 Gutyar's (1955) Wheel in Elasto-Plastic Ground

Combining equations (113), (112), and (111), simplifying trigonometric functions, and expanding them into series, Gutyar obtained upon integration, the following relationship:

$$W = \frac{D^2 b}{2\pi^2}\left[k_G \alpha_1^3 + k_G^1 \alpha_2^3 \right] \tag{114}$$

Since from equation (110),

$$\frac{k_G}{k_G^1} = \frac{z_1 - z_2}{z_1} \tag{115}$$

and from wheel sinkage geometry,

$$z_1 = \frac{D}{2}(1 - \cos \alpha_1)$$

$$z_2 = \frac{D}{2}(1 - \cos \alpha_2)$$

Equation (115) shows upon transformation and the development of the trigonometric functions into series, that

$$\frac{k_G}{k_G^1} = \frac{\alpha_2^2}{\alpha_1^2} \tag{116}$$

or,

$$\left.\begin{aligned} \alpha_2 &= \alpha_1 \sqrt{k_G/k_G^1} \\ \alpha_1 &= \alpha_2 \sqrt{k_G^1/k_G} \end{aligned}\right\} \tag{117}$$

Combining equation (117) with equation (114) gives:

$$\left.\begin{aligned} \alpha_1 &= 3\sqrt{\frac{2\pi^2 W}{D^2 b k_G \left(1 + \sqrt{k_G^1/k_G}\right.}} \\ \alpha_2 &= 3\sqrt{\frac{2\pi^2 W}{D^2 b k_G^1 \left(1 + \sqrt{k_G/k_G^1}\right.}} \end{aligned}\right\} \tag{118}$$

Motion resistance R may be determined in a similar manner:

$$R = \frac{Db}{2} \left[\int_0^{\alpha_1} p_1 \sin \alpha \, d\alpha - \int_0^{\alpha_2} p_2 \sin \alpha \, d\alpha \right] \tag{119}$$

Combining equations (119), (112), (111), and (118) led Gutyar, upon transformation and expansion of trigonometric function into series, to the following equation:

$$R = \frac{0.765 W^{4/3} [1 - (k_G/k_G^1)]}{[1 + \sqrt{k_G/k_G^1}]^{4/3} [k_G D_b^2]^{1/3}} \tag{120}$$

Values of k_G and k_G^1 must be calculated from tests with the same wheel. If angles, α_1 and α_2 are measured, then ratio k_G/k_G^1 may be determined from equation (116). The same ratio may be determined from equation (115), if sinkages z_1 and z_2 are experimentally determined. Writing equation (114) in the form:

$$W = \frac{D^2 b}{2\pi^2 k_G^1} \left[\frac{k_G}{k_G^1} \alpha_1^3 + \alpha_2^3 \right] \tag{121}$$

enables one to determine k_G^1, and hence k_G. Thus the test requires measuring W, R, α_1, α_2, or z_1 and z_2 in order to define k_G and k_G^1, assuming that the soil displays $n = 1$.

What Gutyar has not shown was proof that k_G and k_G^1 are really independnet of W, for the same wheel and soil, and for soil with $n \neq 1$. His work also raises a "teleological" question: why the testing of the soil by means of the same wheel whose load and motion resistance will be predicted?

Gutyar apparently did not aim at establishing some sort of test-instrument/wheel-performance correlation independent of instrument size and load. Like Letoshneve, he preferred to use the actual wheel as a test apparatus and to describe the test results in mathematical form whose value was limited, in the best case, to the description of performance of the tested wheels.

Gutyar and Vernikov's work exemplifies the post-Letoshnev school of thought. It also proves that until the nineteen fifties attempts to improve Bernstein-Letoshnev's equations

by adding more assumptions, instead of revising the existing ones, were most popular.

Such revision took place not in Russia but in the United States (Bekker, 1955a), almost at the same time when Gutyar published his paper. The new development was not known, in all probability, to the Russian engineers until it was published in the professional journal two years later (Bekker, 1957). Thus the prior and the intermediate periods were characterized by the trend in which little practical progress was made, though theoretical investment was sizeable.

It would be unfair to say, however, that Russian theoretical progress was always based on dumping more assumptions onto existing assumptions. Rational analyses leading to clarification of the fundamental issues, such as for instance the kinematics of the wheel and soil particles in motion, were also taking place.

The often quoted Academician Goryachkin (1937) assumed a long time ago that soil particles were moving along orthogonal lines to the rim surface. However, Zeligovski (1950) observed that with slip or skid, the directions of soil compression deviate from the normal to the rim. Andreev (1953) undertook a careful study of the problem, and reported the results in a comprehensive paper (Andreev, 1956). Similar work was performed by Vasilenko (1950). He derived analytical expressions for soil displacement, considering particle sliding along the certain portions of wheel rim, but as Andreev (1956) put it "completely ignored the shape and equations of the trajectories of particle motion in compression." To correct this deficiency Andreev examined the whole problem.*

He considered both positive (skid) and negative slip for rigid wheels with flat and convex rims, the latter formed by a rounded surface imitating a tire. In the present analysis only negative slip of a driven wheel and a flat rim will be considered, since this provides a simple description of the method and a sufficient basis for conclusions.

* The stress isocline and shear surface problem in soil under static loading areas, has been solved since the early twenties and was known to Russian soil mechanic scientists (Sokolovskii, 1942). General rules apply to moving loads. Conspicuously, any references to these elementary facts are lacking in Russian automotive and agricultural literature.

A wheel moving with slip i_o follows the instantanous center of rotation 0 which is located on the vertical axis inside the wheel rim (Figure 26a). From the geometrical relationship, the angle γ between the linear speed of point M of the rim, and the radius r located at angle σ were assumed to be:

$$\tan \gamma = \frac{1 + (i_o - 1) \cos \sigma}{(1-i_o) \sin \sigma}$$

or, when using Andreev's definition of the "coefficient of slip η," where $\eta = i_o/(1-i_o)$, the value of $\tan \gamma$ was:

$$\tan \gamma = \frac{(1 + \eta) - \cos \sigma}{\sin \sigma} \tag{122}$$

Angle γ reaches a minimum when $\sigma = 1/(1+\eta) = \sigma_1$ (Figure 26b). For the coefficient of friction μ_o between the wheel and the soil, if $\tan^{-1}\mu_o > \sigma_1$, there are two points, A_2 and A_3, defined by angles σ_2 and σ_3, where $\gamma = \tan^{-1}\mu_o$, or $\sigma_2 + \sigma_3 = 2\tan^{-1}\mu_o$. Arc O' O" may be thus divided in three sections:

$$\begin{array}{llll} \text{I.} & \sigma_2 < \sigma \leq \sigma_o & \text{where} & \gamma > \mu_o \\ \text{II.} & \sigma_3 < \sigma \leq \sigma_2 & \text{where} & \gamma \leq \mu_o \\ \text{III.} & O < \sigma < \sigma_3 & \text{where} & \gamma > \mu_o \end{array} \tag{123}$$

In sections I and III, soil particles in contact with the rim, slide in the direction of rotation. In section II, there is no relative movement of soil in relation to the rim. The limits of sections I, II, and III are defined by:

$$\sigma_{2,3} = \tan^{-1}(\mu_o) \mp \cos^{-1}\left[(1 + \eta) \cos (\tan^{-1}\mu_o) \right] \tag{124}$$

Andreev calculated values of σ_2 and σ_3 as shown in Table 19.

Table 19

$\tan^{-1}\mu_o$ / η	$< 11^o$	11^o		17^o		22^o		27^o	
	σ_2	σ_3	σ_2	σ_3	σ_2	σ_3	σ_3	σ_3	σ_3
0.02	11	11	11	6	28	4	40	3	51
0.06	20					11	30	9	45
0.10	24							16	38

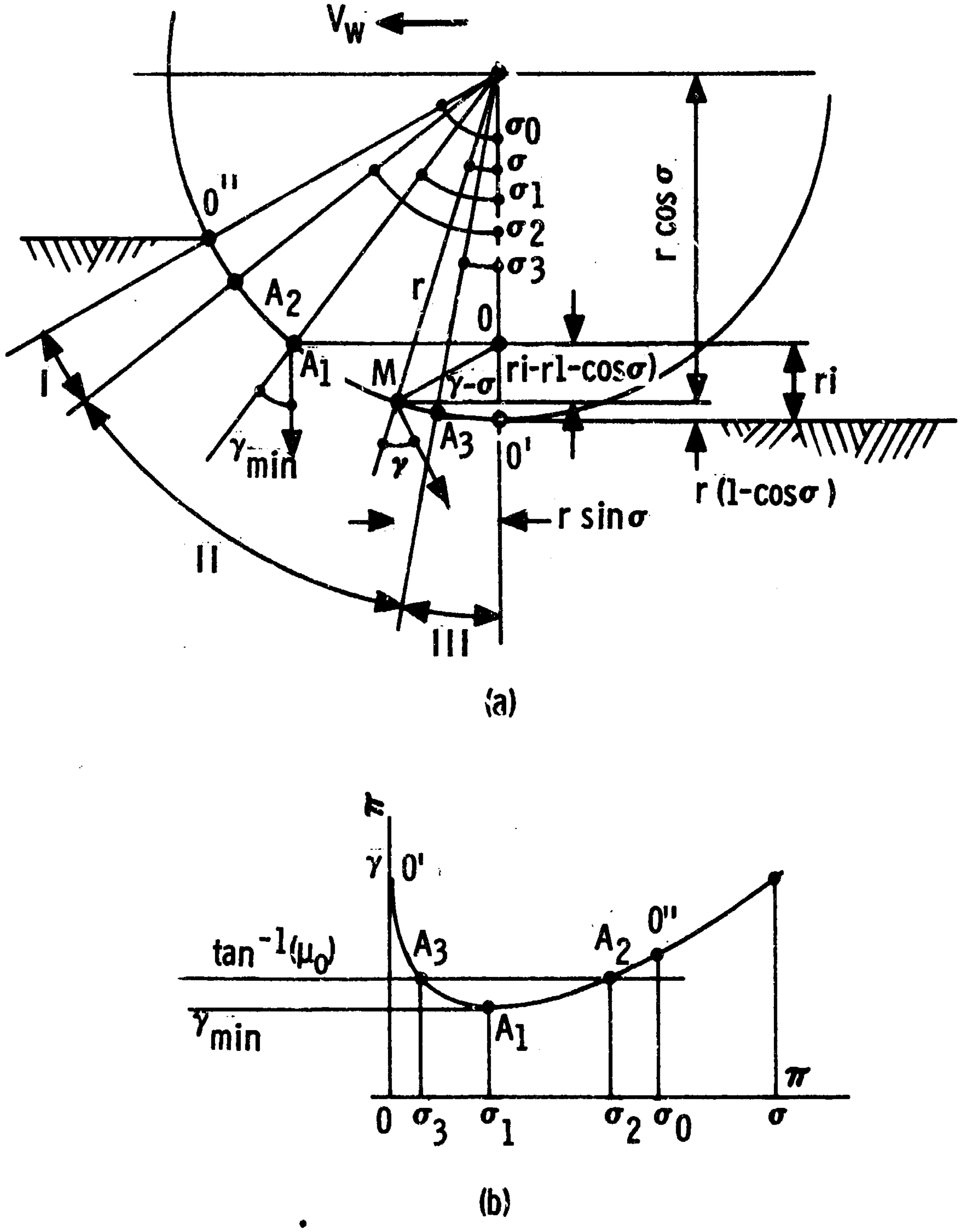


Figure 26 Andreev's (1956) Analysis of Wheel Kinematics

An increase of μ_o at constant η widens zone II and shortens zones I and III (Figures 26 and 26b). When $\sigma_1 = \tan^{-1}\mu_o$, which is equivalent to $\eta = 0.5\ \mu_o^2$, points A_2 and A_3 merge with point A_1. Then, $\sigma_3 = \sigma_2 = \sigma_1$, and soil particles everywhere slide with reference to the rim, except at point A_1. For $\sigma_1 > \tan^{-1}\mu_o$ the division of the rim into various zones is nonexistent, and the soil slides relative to the rim at all points.

With the clarification of these kinematic relationships, Andreev proceeded to deduce parametric equations of the downward trajectories of soil-particle movement, adjacent to the rim.

In zones I and III, for $\sigma_1 < \tan^{-1}\mu_o$, the soil pressure is not normal to the rim, but deviates from normal by the angle of friction $\tan^{-1}\mu_o$, in the direction of wheel rotation. Thus the tangents to the trajectories of "soil compression" were assumed to be inclined to the horizontal by the angle of $90 - \sigma + \tan^{-1}\mu_o$ (Figure 27a). Accordingly, the tangent was:

$$\frac{dy}{dx} = \cot(\sigma - \tan^{-1}\mu_o) \tag{125}$$

But

$$y = r(1 - \cos\sigma) \tag{126}$$

and

$$dy = r \sin\sigma \, d\sigma \tag{127}$$

Substituting equation (127) in equation (125) gives:

$$dx = r \sin\sigma \tan[\sigma - \tan^{-1}\mu_o]\, d\sigma \tag{128}$$

Integration of equation (128) and equation (127) yields:

$$\begin{aligned} x &= r\left[\cos(\tan^{-1}\mu_o)\, \ln\tan\left(\frac{\pi}{4} - \frac{\tan^{-1}\mu_o}{2} + \frac{\sigma}{2}\right) - \sin\sigma\right] + C \\ y &= r(1 - \cos\sigma) \end{aligned} \tag{129}$$

Equations (129) represent, in the parametric form, the trajectories of particles in contact with the rim, in zones I and III. C is the integration constant depending on the choice of the location of the y-y axis.

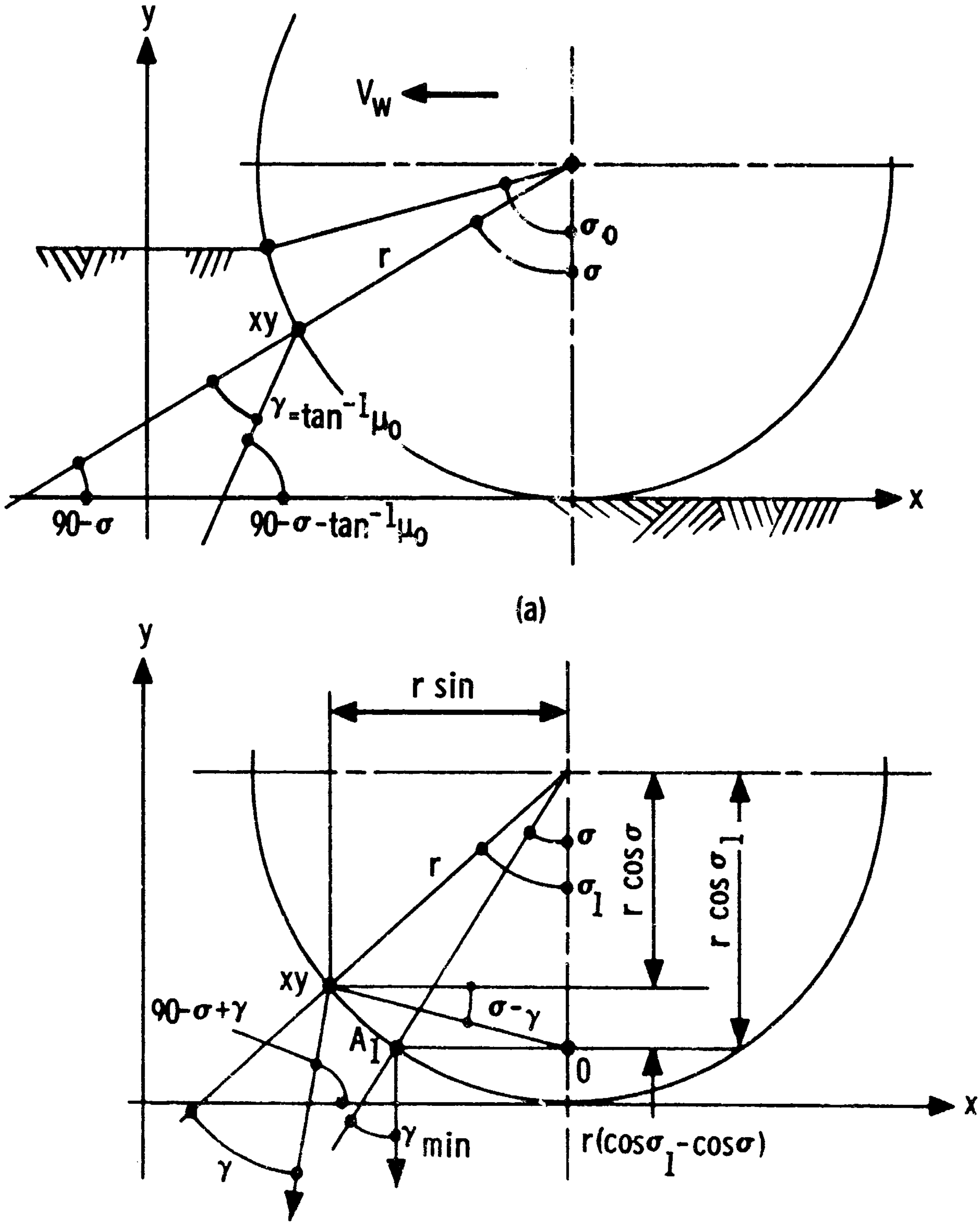


Figure 27 Geometry for Trajectories of Soil Movement under Wheel Compaction (Andreev, 1956).

In zone II, "soil compression" by the rim takes place in the direction of motion of the given point whose tangent to the trajectory also is inclined to the abscissa at an angle, $90 - \sigma + \gamma$. However, $\gamma < \tan^{-1}\mu_o$, as previously defined, and from Figure 27b:

$$\frac{dy}{dx} = \cot(\sigma - \gamma) \tag{130}$$

or

$$\frac{dy}{dx} = \frac{\sin\sigma}{\cos\sigma_1 - \cos\sigma} \tag{131}$$

if angle σ_1 is introduced (Figure 27b). Note that as previously explained σ_1 defines γ_{min}, in which case $\cos\sigma_1 = 1/(1+\eta)$. Figures 26 and 26b, and Figure 27b denote the location of point A_1 with reference to the momentary center of rotation O.

Since $y = r(1 - \cos\sigma)$, and $dy = r\sin\sigma\, d\sigma$ (see equations 126 and 127), equation (131) yields:

$$dx = r(\cos\sigma_1 - \cos\sigma)\, d\sigma \tag{132}$$

Integration of equation (132) and equation (126) gives the parametric equations of the trajectories in zone II:

$$\left.\begin{aligned} x &= r(\sigma\cos\sigma_1 - \sin\sigma) + C \\ y &= r(1 - \cos\sigma) \end{aligned}\right\} \tag{133}$$

The trajectories, equations (129), and (133), were computed by Andreev for a driven wheel for $\tan^{-1}\mu_o = 31^o$ and $\eta = 0.14$, i.e., for slip $i \cong 12.4\%$ (Figure 28a).

Similiar computations were made for a skidding (towed) wheel involving "skid coefficient" $\epsilon = \frac{i_o}{i_o - 1}$, equivalent to: $-\eta$.

Andreev's solutions for wheel rims of a thoroidal shape (pneumatic tire) were so complex in form and applicational procedures, that only a great gain in their predictive capability would justify their use. Thus the general question arises if the fine mathematics shown in the analysis of wheel kinemetics, in equations (122) to (129), would help to obtain better practical results than the old Bernstein-Letoshnev solution, and at what cost. The answer will be forthcoming from further analysis of work by Andreev.

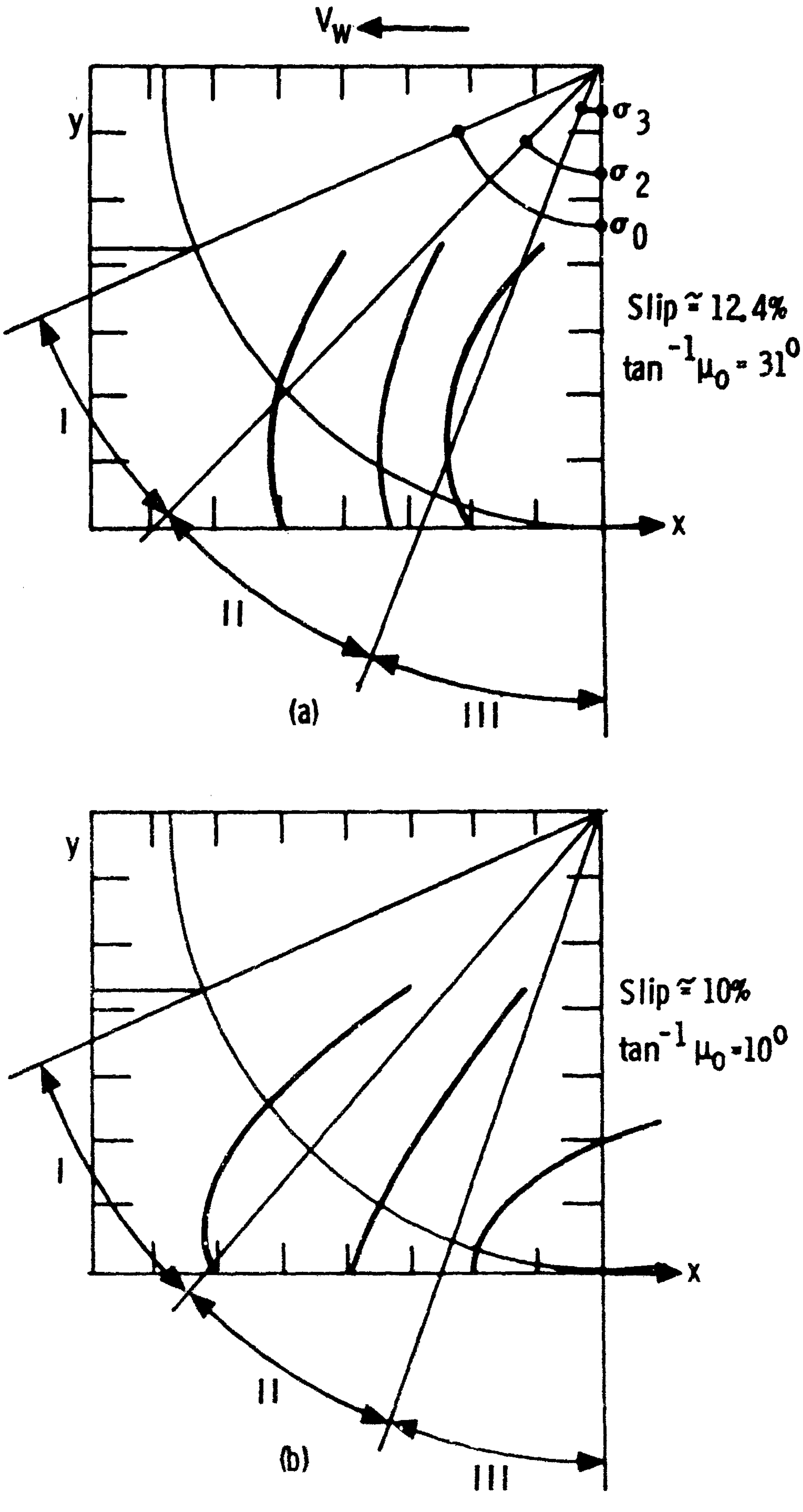


Figure 28 Andreev's (1956) Trajectories of Soil Compression Which Define the Path of Particles Adjacent to Wheel Rim.
a. Driven wheel; b. Towed Wheel

The purpose of determining the trajectories of "soil compression" as traced by the movement of particles immediately adjacent to the rim was to find the length of the path of "compression" ℓ :

$$\ell = \sqrt{dx^2 + dy^2} \tag{134}$$

Assuming that the force of compression follows Bernstein-Letoshnev's law $p = k\ell$, the pressure acting on the given elementary portion of the rim in zone II was expressed for a driven wheel (Figure 27a) as:

$$p_{II} = k\ell = kr \int_{\sigma_o}^{\sigma_2} \left[(\cos \sigma_1 - \cos \sigma)^2 + \sin^2 \sigma \right]^{1/2} d\sigma \tag{135}$$

upon combining equations (128) and (127) with (134).

Similarly for zone I and III:

$$p_{I,III} = kr \int_{\sigma_o, \sigma_3}^{\sigma_2, 0} \left[\sin^2 \sigma \tan^2 (\sigma - \tan^{-1} \mu_o) + \sin^2 \sigma \right]^{1/2} d\sigma \tag{136}$$

To obtain compression forces, i.e., the motion resistance R, pressures p_{II} and $p_{I,III}$ had to be integrated again along their respective lengths of rim portions:

$$P_{I,II,III} = \int_{\sigma_o, \sigma_2, o}^{\sigma_2, \sigma_3, \sigma_3} p_{I,II,III} \, ds \tag{137}$$

Next, forces p had to be projected in the horizontal direction in order to obtain R. Andreev's conclusion was that:

> "In this way an improvement in the Grandvoinet-Goriachkin (Bernstein-Letoshnev) formula may be expected, even though it may be at the expense of introducing (additional) friction coefficient μ_o, and coefficients for skid ϵ, and for slip η."

In order to contest or confirm this claim the performing of proper experiments was required. This was never done as far as could be ascertained. Janosi (1963), who performed much later in the United States a similar analysis of wheel kinematics, with full cognizance of Andreev's work, rejected his approach to the subdivision of the rim in various frictional zones. He assumed that $\mu_o \cong 0$, and considered straight cycloidal motion of the wheel rim points that produced horizontal and vertical soil

displacement. Note that Andreev considered the same displacements caused by his cycloids distorted by μ_o.

Soltynski (1962), in Poland, dwelled on identical problems but only analyzed the well known regular cycloidal paths of points located on a wheel rim, considering slip i_o. The article's format had no relation to the depth of Andreev's study. In a book published somewhat later, Soltynski (1965) discussed Andreev's "zones" (no reference given) with good clarification, and elaboration of problems involved. But Soltynski did not espouse Goryachkin-Grandvoinet's formula $p = k\,\ell$. Instead, he adopted American solutions (Bekker, 1956, 1960): $p = [k_c/b) + k_\varphi]\, z^n$.

Sitkei (1966) worked in Hungary on similar problems. He dwelled extensively on Andreev's work without mentioning it either in the text or in the references. He also seems to have confused ϵ and η with $\pm\, i_o$. Nevertheless he proceeded methodologically in the manner very similar to that by Andreev, noticing that zone II (Figure 28) is not large; therefore he assumed that elementary soil reaction vectors deviate from wheel radius by $\tan^{-1}\mu_o$ — in all zones. Sitkei further considered Letoshnev's equation $p = kz^n$, assuming $n \neq 0$; his avoiding the "zoning" simplified the solutions.

Apparently he performed experimental verification of Andreev's and his theory, and found that slip measured in sand was greater than theoretically predicted. This he explained by the fact that considering rim-soil friction (μ_o) alone does not account for soil shear around the wheel-rut configuration, and illustrated this is a primitive sketch of soil particle movement.

Since the Andreev-Sitkei equation does not include the angle of ainternal soil friction φ, it cannot portray the true shear pattern of soil under wheel action, and hence the wheel performance. Classical experimental data by McKibben and Green (1940) were undoubtedly available to Andreev, since they were widely disseminated by the foremost U. S. agricultural professional publication. However the publication had no effect upon Andreev-Sitkei, or even on Janosi's work, though the data contained a meticulous study of motion of soil particles under wheel action. Perusal of this information alone would have shown immediately that the "piece de resistance" in wheel performance is not soil-rim friction μ_o, but the shear pattern, deep in soil mass.

Experiments by Bekker (1948), performed in Canada, replicated independently McKibben's and Green's data, using a quartz grid, instead of the buried markers technique (see Bekker, 1969, Part II, Figures 2-14 and 2-15). Soil deformation pattern thus enabled this writer to trace the trajectories of principal stresses and the shear pattern, using Haefeli's technique (see Bekker, 1956).

This technique also was applied to McKibben's and Green's data (Bekker, 1951), and the shear pattern thus obtained was shown in Figure 29. Photographic experiments with the soil particle movement under wheel action, (Figure 30) by Wong and Reece (1966), admirably confirm the theoretical data obtained by means of Haefeli's method.

Now a comparison between Figures 28 and 29 poignantly shows what Andreev missed and what Sitkei indirectly anticipated (also see Sitkei, 1967). Incidentally, mathematical solutions for tracing the shear pattern, Figure 29, have been available since Prandtl (1920), Terzaghi (1943), and Sokolovskii (1942).

This writer was convinced, on the basis of the described tests performed almost two decades ago, that further dwelling on trajectory determination will only disclose what could have been expected since Prandtl and Terzaghi, at least for practical purposes. Most recent tests by Windisch and Young (1970), performed with great expense and scarce funds and time, have indirectly confirmed that conclusion again.

These students of the problem repeated the old experiments by McKibben and this author, adding velocity distribution along the trajectories in a search for stress fields. They concluded that:

> "application of knowledge gained from examination of strain rate behavior of soil under moving wheel must necessarily await the development of admissible constitutive relationship for soil.... Such information could possibly provide the basis for comparison between wheels and wheel performance using like or unlike generated strain rate fields."

"We must then await" more information to evaluate wheels, using these methods. And in the best case the "information could possibly provide only a basis" for wheel evaluation.*

* The authors of field equations for soil-wheel performance do not seem to realize that the nonhomogeneity of soil will make such equations practically useless, even in the event they solve all other problems.

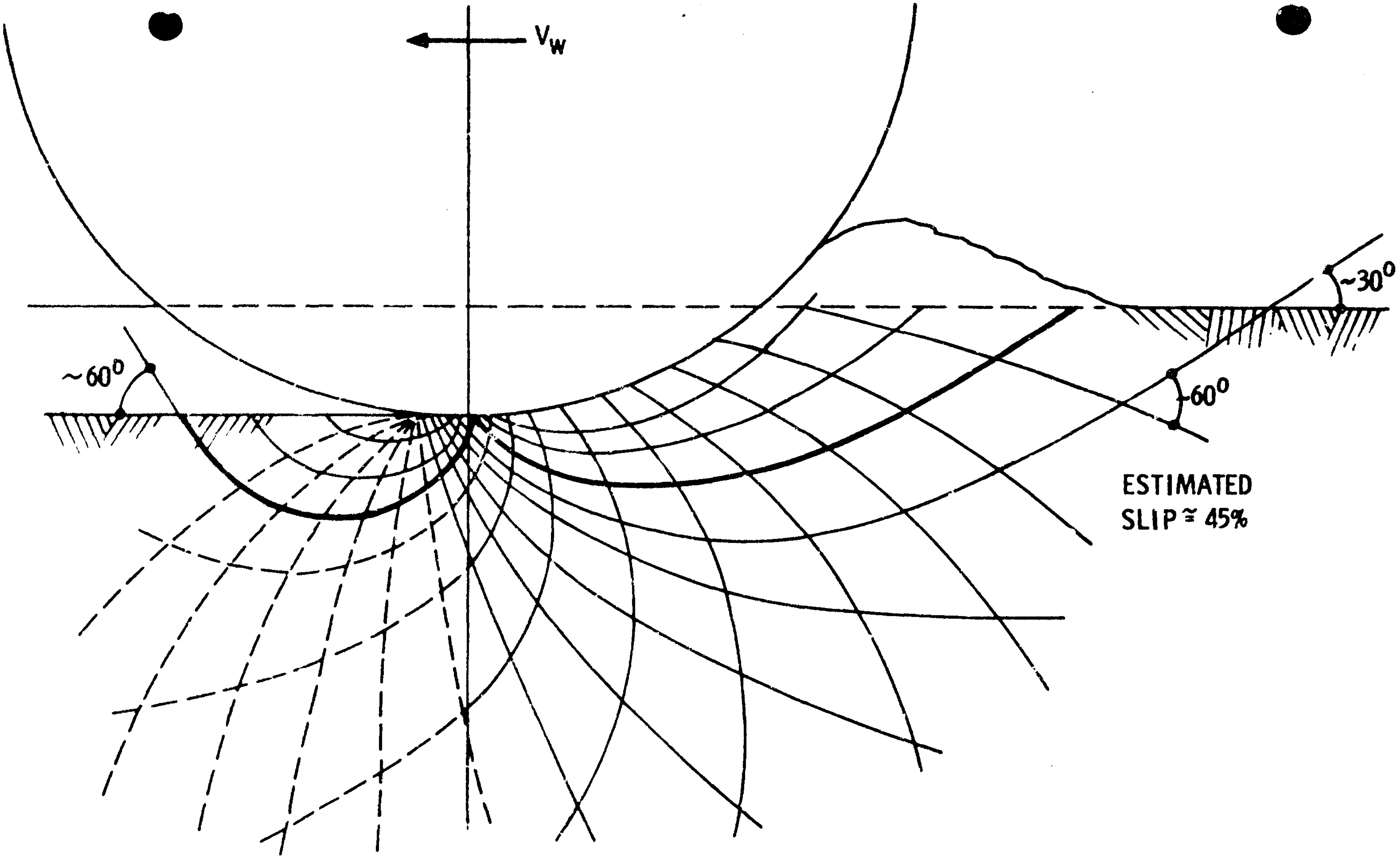


Figure 29 Shear planes of a 6 in. wide towed steel wheel with 28" dia. under 1000 lb. in Des Moines sand. The planes were construed by Bekker (1951) using Haefeli's method and sand particles displacement determined experimentally by McKibben and Green (1940).

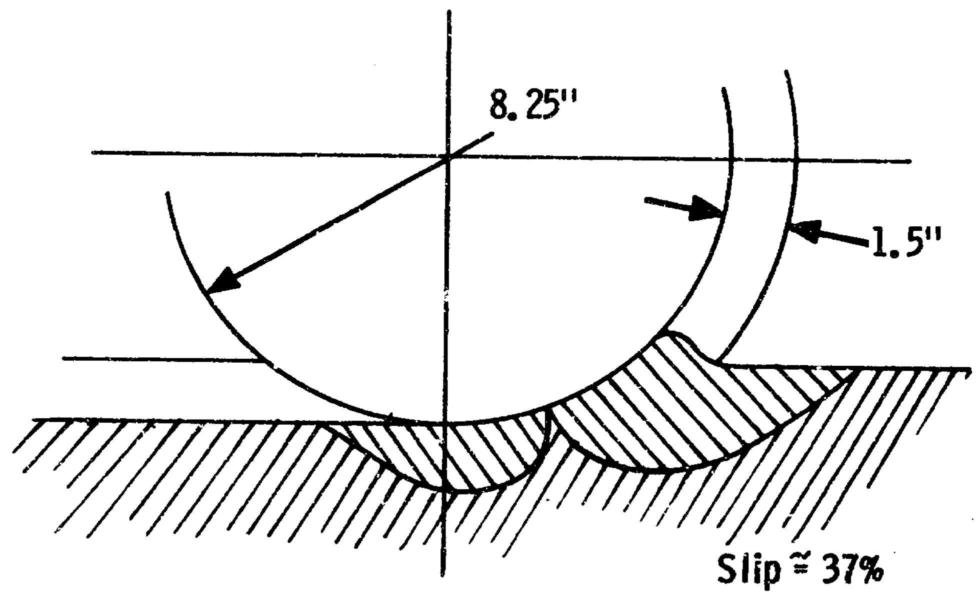


Figure 30 Outline of the wheel and the envelopes of sand particle movements, photographed by Wong and Reece for a towed wheel. Copy of Figure 9 A from Wong and Reece (1966).

This academic message of 1970 cannot be accepted by engineers who have worked on the problem since 1913 and built billions of wheels for on- and off-road locomotion. It should be sobering for everyone concerned that the Russians have not wasted talent and money for such self defeating purpose. For the cost has never been worth the payoff.

The lesson of this case study is simple: before undertaking theoretical analyses, see what really matters. Otherwise there is always the danger of laboring on a fine solution under unimportant, or academic assumptions. Andreyev, Sitkei, and the others seem to have fallen in this trap, and many still do.

In general, the Russian studies on wheel-soil interaction up to 1956 were not quite compatible with practical and experimental evidence. They aimed at a "theoretical" improvement of Bernstein-Letoshnev's equation by merely adding to that equation new assumptions and amplifications.

American work performed at that time by the Land Locomotion Laboratory in Detroit had a much sounder basis for theoretical wheel analysis. This started with the total re-examination of Bernstein-Letoshnev's equation, which led to the substitution of k_B and/or k_L values with $k = (k_c/b) + k$ (Bekker 1955, 1957, 1960). Such approach was an evolutionary process of the early German and Russian developments, to which other studies of soil mechanics have distinctly contributed, including those by the late Professor D. E. Taylor (1948) of M. I. T.

As usual, the dissemination of the new approach to soil values took a long time; thus the Russian agricultural and automotive engineers proceeded within the established framework which neglected not only the progress abroad, but also their own attempts, including those by Gutyar, Andreev, and the others.

Hence Vasilevich (1959) further considered, with a substantial dose of pessimism, Goryachkin's equation (108) for motion resistance of the wheel. Academician M. E. Matsepuro (1960) again quoted the same equation, and referring to research by "Professor Letoshnev again (noted) that n-value should be taken as 0.5 instead of a unit."

Matsepuro, however, also was concerned with turf soils, covered or not with a heavy layer of grassy vegetation, where the $p = kz^n$ formula required modification, as discussed in Chapter II and in reference by Bekker (1969). This led to a semiempirical wheel analysis briefly described as follows:*

- the 3 to 6 times greater resistance to penetration, than the penetration resistance of the turf without the cover
- the tensile strength of the cover 4 to 8 times larger than that of turf
- the shearing strength of the cover, in vertical direction, 3.5 to 4 times larger than the strength of turf
- the shearing strength of the lower layer of the cover in a horizontal direction, 1.2 to 1.4 times stronger than the strength of turf.

This clearly established a two-layer structure where $p = kz^n$ function could not be accepted, and tests performed with turf showed, according to Matsepuro, that equation (18) attributed here to Korchunov holds well for grass- or moss-covered turf. The equation implies that bearing strength of such a layered organic mass depends on the shear along the perimeter of the loading area and on the resistance to penetration. Note that Mayerhoff (1960, 1962) and others made similar assumptions for ice and concrete pavements, which were later adapted by Bekker (1969) to land locomotion on tundra, muskeg, and other two-layer "soils."

For the Russian turf, Matsepuro quoted the following tentative data (Table 20):

Table 20

Terrain	Tentative Strength (kg/cm^2)		Rupture Strength* (kg/cm^2)
	Tensile	Shear	
Turf	0.022 - 0.026	0.09 - 0.17	0.75 - 1.75
Grass Sod	0.10 - 0.20	0.36 - 0.68	2.00 - 7.10

* Measured with penetrometer plate of 10 cm^2

In this type of material several wheel tests were made. They reportedly confirmed perimeter-shear and area-penetration principles. Relationship between sinkage z,

* Note the uselessness of the "field theory" advanced by Windish and Yong (1970), in this kind of "soil."

wheel load W, and wheel dimensions D, b was then defined by the following equation:

$$z = \left[\frac{3W}{k_t\,(3-n)\,(b_m+b)\sqrt{D}}\right]^{\frac{2}{2n+1}} \tag{138}$$

where k_t was the modulus of turf deformation and b_m was a coefficient related to shear and compression strength of the "soil," which apparently included the perimeter-load area relation, Table 20.

The derivation of this equation was not given. However, it is strikingly similar to Bekker's (1957, 1960) equation for rigid wheel sinkage in a "regular" homogeneous soil:

$$z = \left[\frac{3W}{(3-n)\,(k_c+bk_\varphi)\sqrt{D}}\right]^{\frac{2}{2n+1}} \tag{139}$$

The difference lies in the soil values, which was to be expected. However, it could be surmised that:

$$k_t\,(b_m+b) \sim k_c+bk_\varphi \tag{140}$$

or

$$\left.\begin{array}{l} k_t b_m \sim k_c \\ k_t \sim k_\varphi \end{array}\right\} \tag{141}$$

Thus the similarity of the approach by the Russian and American schools was striking, indeed. This was further demonstrated by equations for motion resistance and turf meadows:

$$\text{(Matsepuro)} \qquad R = \frac{k_t\,(b_m+b)}{1+n}\left[\frac{3W}{k_t\,(3-n)\,(b_m+b)\sqrt{D}}\right]^{\frac{2n+2}{2n+1}}$$

Similarly, for homogeneous soil: (142)

$$\text{(Bekker)} \qquad R = \frac{(k_c+bk_\varphi)}{n+1}\left[\frac{3W}{(3-n)\,(k_c+bk_\varphi)\sqrt{D}}\right]^{\frac{2n+2}{2n+1}}$$

Values of k_t and b_m were not available; n was given as varying between 0.05 and 0.25 for mud-type turf. In any case, it was stressed that $n < 0.5$.

Experimental values were usually higher than those calculated from equations (139) and (142) by means of sinkage measurements with wheels. This was explained by considerable shear and bulldozing of the vegetation in the front of the wheel. The critical wheel load, W_{crit}, below which such a bulldozing was avoided, had been determined experimentally by:

$$W_{crit} = m_1 + m_2 bD \tag{143}$$

where m_1 and m_2 were empirical coefficients depending on turf cover. One of the most difficult turf conditions was defined by $m_1 = 660$ kg and $m_2 = 0.25$ kg/cm^2. To ensure the trafficability, wheel load W should be selected with a safety factor f_s from 1.5 to 2.0 according to relation:

$$W = W_{crit}/f_s \tag{144}$$

These wheel studies are in sharp contrast with the previously discussed studies of wheel kinematics. Instead of trying to improve Bernstein-Letoshnev equations by means of speculative additional assumptions alleging a "scientific" treatment of the problem, the Russian agricultural engineers of the Minsk School took Bernstein-Letoshnev's equations as they were, and tried to improve the accuracy of predictions by empirical corrections obtained in the field. Their goal was not an academic dissertation but a practical solution. Such a pragmatic process of technological advance in off-road locomotion does not seem to have found recognition in the United States, even at the time of writing this critique.

An interesting aspect of engineering simplification without theoretical impertinence was the treatment of motion resistance. Research reportedly performed by N. I. Klenin at the Department of Soil Working Machinery of the Minsk Institute of Mechanization and Electrification of Agriculture (Matsepuro and Katsygin, 1961) made it plausible to assume that soil reaction R_s of a towed wheel acts as a bisector of angle 2α (Figure 31). Thus $\cos 2\alpha = (r - z)/r = 1 - 2z/D$. But

$$\cos \alpha = \sqrt{(1 + \cos 2\alpha)/2}$$

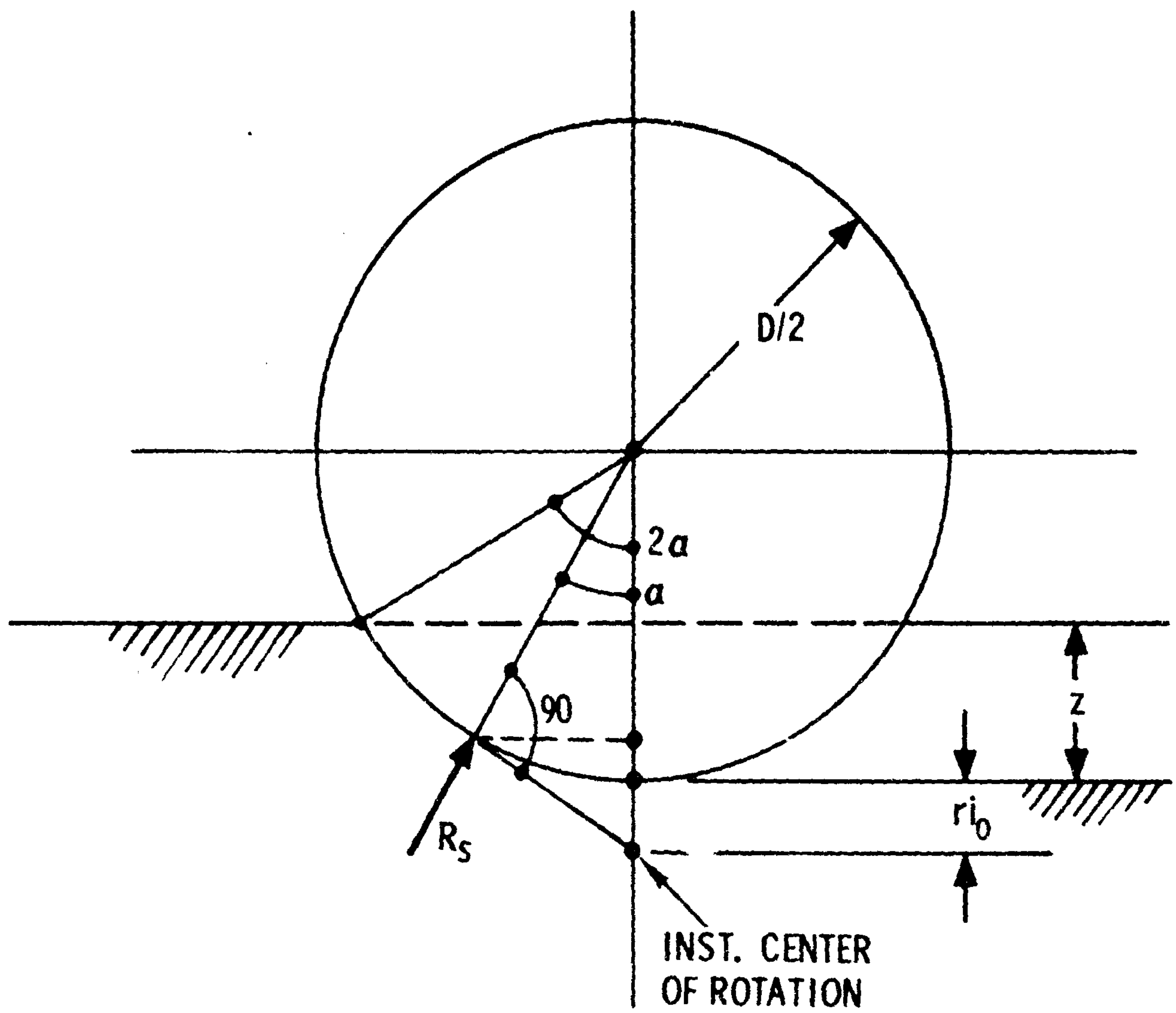


Figure 31 Geometry of Wheel Slip

hence,

$$\cos\alpha \cong \sqrt{1-(z/D)} \tag{145}$$

On the other hand, $r\,i_o + r = r\cos\alpha$, or:

$$i_o = 1 - \cos\alpha \tag{146}$$

Combining equations (145) and (146) gives:

$$i_o \cong 1 - \sqrt{1 - z\,(z/D)} \tag{147}$$

The accuracy of this equation is approximate, but it gave good results for low sinkage. Sh. F. Margolin of the Belorusyau Academy of Agricultural Sciences deduced the following formula for unit wheel resistance $f = R/W$:

$$f = \frac{3}{(1+n)(3-n)} \sqrt{\frac{z}{D}} \tag{148}$$

Value of n for soft soils was, as usual, $0 < n < 1$. The derivation of equations (147) and (148) was not given. It is obvious, however, that Margolin's equation is directly related to Bekker's formulae for resistance R, equation (142), and for sinkage z, equation (139).

Professor Matsepuro and Yanushkevich, and Matsepuro and Svirshchevskii (1961), quoted extensive passages from Bekker (1956), adding Russian denotations of soil values discussed in Chapter II; they dwelled, however, on Letoshnev's four-wheel carriage performance. Kinematics of a rigid wheel, including Andreev's (1956) division of wheel rim into various frictional zones, was also for the first time included in the "Voprosy..." Since the authors concentrated on turf-moss type soils, they modified Bernstein-Letoshnev's equation (5) by the inclusion of the Housel equation (18) as discussed in Chapter II. Hence, for the above "soils" they assumed that:

$$p = \left(A_o + B_o \frac{U}{A}\right) z^n \tag{149}$$

Tests showed that n varied between 0.36 and 0.42. Equation (149) served as a spring board for deduction of motion resistance formulae.

From Figure 32, perimeter of the shear area approximately equals $2\,i_o r$, and the area is $b i_o r$, where b is wheel width. Hence equation (149) takes the following form:

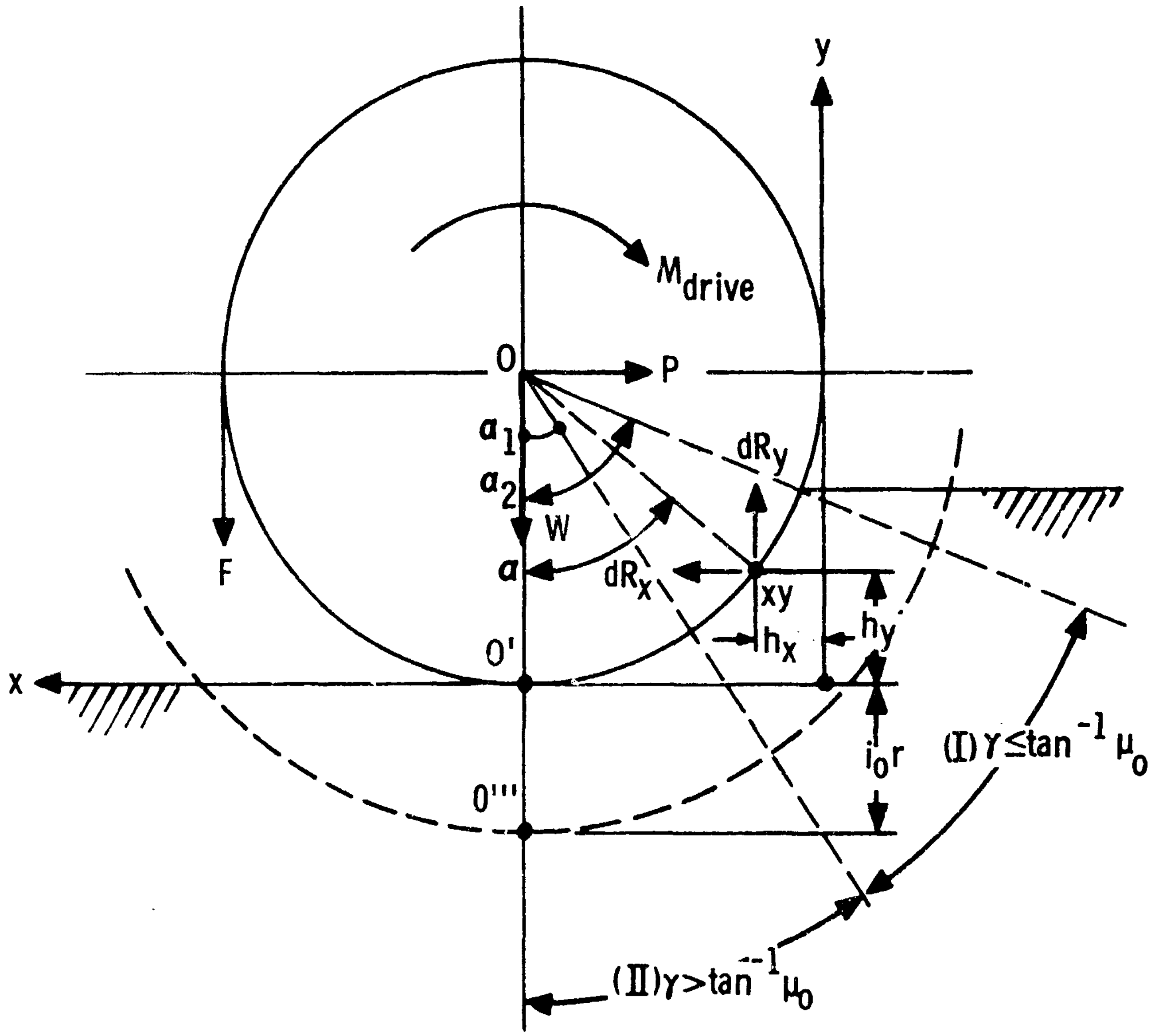


Figure 32 Forces and geometry diagram of a driven wheel
(adapted from Matsepuro and Yanushkevich, 1961)

$$p = \left(\frac{A_o b + 2 B_o}{b} \right) z^n \tag{150}$$

For zone I (no slip of soil particles along the rim):

$$\begin{aligned} h_x &\simeq (r + i_o r) \alpha - r \sin \alpha \\ h_y &= r - r \cos \alpha \end{aligned} \tag{151}$$

It was assumed that equations (151) fit Bernstein-Housel's $p = kh^n$ (which this writer would strongly question, at least for h_x, without empirical evidence that was not available). Under these circumstances:

$$\begin{aligned} p_x &= \frac{A_o b + 2B_o}{b} \left[(r + ri_o) \alpha - r \sin \alpha \right]^n \\ p_y &= \frac{A_o b + 2B_o}{b} \left[r - r \cos \alpha \right]^n \end{aligned} \tag{152}$$

In a similar manner, for Zone II, where Andreev's angle γ of wheel reaction is larger than the angle of turf-rim slip, $\varphi_s = \tan^{-1} \mu_o$ and:

$$\begin{aligned} h'_x &= (r + ri_o) \alpha - r \sin (\alpha - \varphi_s) \\ h'_y &= r - r \cos (\alpha - \varphi_s) \end{aligned} \tag{153}$$

and

$$\left.\begin{aligned} p'_x &= p_x + \left[- \frac{A_o b + B_o}{b} \right] \left[(r + ri_o) \alpha - \sin (\alpha - \varphi_s) \right]^n \\ p'_y &= p_y + \left[\frac{A_o b + B_o}{b} \right] \left[r - r \cos (\alpha - \varphi_s) \right]^n \end{aligned}\right\} \tag{154}$$

Integrals of elementary reactions of the turf ground at point (xy) are:

$$R = \int p \, b \, r \, d \alpha \tag{155}$$

Substituting in Equation (155), equations (152) and (154), and integrating respective functions (Zone I) from α_1 to α_2, and (Zone II) from O to α_1, it will be obtained that:

$$R_x = \frac{(A_o b + 2B_o)\, r^{n+1}}{n+1} \left[(\alpha_2^{\,n+1} - \alpha_1^{\,n+1}) \; (i_o - 1)^n \right]$$
$$R_y = (A_o b + 2B_o)\, r^{n+1} \left[(\alpha_2 - \alpha_1)(1 - n) \right] \tag{156}$$

$$R_x^1 = (A_o b + 2B_o) r^{n+1} \left[\frac{\alpha_1^{\,n+1} \, (i_o - 1)^n}{n+1} \right] + (A_o b + 2B_o) r^{n+1}$$
$$+ \left[\frac{\alpha_1^{\,n+1} (i_o - 1)^n}{n+1} + i_o^{\,n-1} \, \alpha_2 \varphi_s \right]$$
$$R_y^1 = (A_o b + 2B_o)\, r^{n+1} \left[\alpha_1 \, (1-n) + (A_o b + 2B_o)\, r^{n+1} \right.$$
$$\left. \times \, (\alpha_1 - n \alpha_2 + \frac{n \varphi_s \, \alpha_2}{2}) \right] \tag{157}$$

By adding R sub x's and R sub y's, the motion resistance R and wheel load W will be obtained; from Figure 32:

$$\Sigma R_x - P = 0$$
$$\Sigma R_y - W - F = 0$$
$$\Sigma M = 0 \tag{158}$$

where F is the force needed for implement towing reduced to wheel rim.

Substituting equations (156) (157) in equations (158):

$$p = (A_o b + 2B_o) r^{n+1} \left[\frac{(\alpha_2^{\,n+1} + \alpha_1^{\,n+1}) \; (i_o - 1)^n}{n+1} \right] + i_o^{\,n-1} \, \varphi_s \, \alpha_1^{\,n} \tag{159}$$

$$W = (A_o b + 2B_o)\, r^{n+1} \left[(\alpha_2 + \alpha_1) \; (1 - n) + \frac{n \varphi_s^{\,2} \, \alpha_1}{2} \right] - F \tag{160}$$

Equations (159) (160) merit attention, irrespective of the validity of the assumptions on which they were based because they include both the slip i_o and the angle of friction φ_s between wheel rim and the organic soil.

An interesting form of unit motion resistance $f = R/W$ was obtained from equations (159) and (160)

$$f = \frac{P}{W} = \frac{(\alpha_2^{n+1} + \alpha_1^{n+1})(i_o - 1)^n + (n+1)\, i_o^{n-1}\, \varphi_s\, \alpha_1^n}{(\alpha_2 + \alpha_1)(1 - n^2) + \frac{n(n-1)\,\varphi_s\,\alpha_1}{2} - \frac{F(n+1)}{A_o b + 2B_o) r^{n+1}}} \tag{161}$$

Also from equation (159) wheel slip was deduced in the following approximate form:

$$i_o \simeq - \left[\frac{(\alpha_2^{n+1} + \alpha_1^{n+1})(A_o b + 2B_o)\, r^{n+1}}{P(n-1)} \right]^{1/n} \tag{162}$$

which has done away with φ_s, and which is unclear.

Innumerable dynamometric tests were reported in the work by Matsepuro and Katsygin (1961). Multitude of data regarding f, w, i_o, R, D, and B were tabulated. Unfortunately no turf parameters A_o, B_o, and n, and angles α_1, α_2 were given in order to check the reliability of the above reported equations.

In all probability the correlation was poor. But the partially referred to mathematical manipulations which presented the new and rather unusual forms for functional relationship between $P(A_o B_o\, b\, \alpha\, i_o\, \varphi_s\, n)$ may serve as an example of an engineering search for solutions based on principles of mechanics.

The weak point of these solutions, stemming from the assumption that $p = kz^n$, was the lack of a more complete system of soil values. It also appears that the introduction of φ_s was an unwarranted luxury, realizing that other errors in the system were much greater than the error of eventual omission of the φ_s.

One thing, however, became obvious: the Minsk School proceeded with a careful evolutionary program, trying to improve what they had at hand rather than to immerse in an endless search for ideal rigorous solutions. This alone was a sign of good leadership, common sense, and economy.

The reader interested in an enormous wealth of engineering data related to performance and design parameters of a rigid wheel in organic "soils" is referred to Matsepuro and Katsygin (1961).

The sober pragmatic, engineering trend of the Minsk School continues until this day. Guskov and Kuzmenko (1964) even tried at one time to solve the problem of a pneumatic tire by substituting it with a larger diameter rigid wheel – an idea originally advanced in the United States (Bekker, 1956). To this end they followed Bernstein-Letoshnev-Bekker equation (47); but the active tire diameter D_R was substituted with the diameter D of the rigid tire in accordance with the relation:

$$D_R = \frac{D\,(c_t + k)}{c_t} \tag{163}$$

as discussed briefly in Chapter I. The problem will be further analyzed in Chapter VI.

Towing performance of a rigid wheel, even equipped with a tread, was described by Guskov and Kuzmenko on the basis of Coulomb and Bernstein-Letoshnev equations. However, the formulae they reported were different from those introduced in the United States by the Land Locomotion Laboratory in Detroit.

Soil thurst $H = \tau ds$ was based on Bekker's equation (1956); the latter however was modified by $\sqrt{j/j_0}$, attributed to work by Babkov, Birulia, and Sidenko (1959), as follows:

$$H = \int_0^s (c + p\tan\varphi)\sqrt{j/j_0}\,ds \tag{164}$$

Here, j was soil shear deformation at the given poir surface contact, and j_0 the deformation at which soil reaches the maximum o shear strength.

The origin of $\sqrt{j/j_0}$ relationship is not known since the Babkov et al. reference was not available. Guskov and Kuzmenko also did not explain the derivation of soil thrust under wheel action, equation (164), though they reproduced, somewhat irrelevantly, a sketch of wheel-forces geometry with a triangular load distribution originally introduced for wheels by Söhne (1958).

Detailed equation for soil thrust was given, presumably after Babkov et al., as follows:

$$H = \frac{br\sqrt{r\,i_0}}{\sqrt{j_0}}\left\{ c\left(\frac{\sqrt{\alpha_0}}{2}\sin\alpha_0 + \frac{1}{\sqrt{\alpha_0}}\sin\frac{^2\alpha}{2}\right) + \frac{k_s r^{n/2}\tan\varphi}{(2.26\sqrt{b})^n}\left(\alpha_0\right)^{\frac{3n-3}{2}}\left(\frac{3}{4} - \frac{5n}{24}\right)\right\} \tag{165}$$

Since the maximum thrust H_{max} takes place at $\tau = c + p\tan\varphi$

$$H_{max} = br \left[c \sin \alpha_o + k_s \left(\frac{r}{2\mathfrak{z}}\right)^n \alpha_o^{2n+1} \left(1 - \frac{n}{3}\right) \tan \varphi \right] \quad (166$$

α_o is the angle which defines wheel sinkage; it corresponds to α_2 on Figure 32; r is wheel radius; coefficient $\mathfrak{z} = 1.13 \sqrt{b r \alpha_o}$. Drawbar pull DP was assumed again in conformity with American work (Bekker, 1956) as:

$$DP = H - R$$

The value of R was defined previously. Optimum slip i_{opt} at which H reaches maximum may be determined from equations (165) and (166). Calculated values of wheel performance for H, R, DP, W, D, b, k_s, n, c, φ, and j_o were produced, but their agreement with experiment was not shown. It appears that all these equations were deduced not necessarily for performance and design parameters prediction. Their aim was tracing functional relationships among various parameters, and their sensitivity, on a relative, comparative basis. This was inevitable because the generalized system of soil values was still non-existent. But it was a good, though indirect, introduction to systems analysis.

It was interesting to note that in the same volume of "Voprosy...", in another Chapter by the same Profe Guskov (1964), the shearing strength of soil in track evaluation was not given in terms of the Babkov et al. formula; it was quoted in the form of the exponential Coulomb-Bekker equation, which was then rewritten using a hyperbolic function described in Chapter II.

Undoubtedly, the years close to 1964 were critical for the redefinition of wheel equations, and the Guskov-Kuzmenko (1964) excursion into Babkov, Birulia, and Sidenko's (1959) work appears to have been a historical one, just for the record.

The real trend toward measuring performance in terms of soil values based on hyperbolic-function became obvious after a series of Bekker's articles published in Machine Design between 1959 and 1960 were translated and republished in Russian, in the Automobilnaya Promyshlennost (Frenkin, 1962).

In the meantime, sporadic attempts at expanding old theories did not entirely cease. As an example, take work by Krasilnikov (1966) from Likhachev Automobile Works, who without saying so tried to generalize Andreev's (1956) wheel rim "zoning" in performance evaluation, by considering steering (towed, pushed, or driven) wheels with cornering forces.

In this manner the two-dimensional analysis by Andreev became a study of the three-dimensional case. It is to the credit of Krasilnikov that he did this with some mathematical simplicity.

His theory, however, had the same deficiency as Andreev's. It was concerned only with trajectories of soil particles adjacent to the wheel rim; hence it could not account for the inevitable, in most cases, deep soil shear. But reportedly the experimental evidence showed the same trend as that by the theoretical calculations. Undoubtedly, the tests were performed in hard soils, at low sinkage.

Since Krasilinkov's study is one of the very rare approaches to the three-dimensional wheel performance,* and particularly to a steering wheel under cornering forces of soil it is briefly described here as a methodological exercise. In conformity with the assumptions equation (129), coordinates of points x y z are (Figure 33):

$$\begin{aligned} x &= r(\varphi - \sin\varphi) \\ y &= r(1 - \cos\varphi) \\ z &= -r\varphi\tan\delta \end{aligned} \tag{167}$$

and angles α, β, defined by tangents to soil particle trajectory at point x y z and the respective axes are:

$$\begin{aligned} \cos\alpha &= \frac{dx}{d\ell} = \frac{r(1-\cos\varphi)}{\sqrt{dx^2 + dy^2 + dz^2}} \\ \cos\beta &= \frac{dy}{d\ell} = \frac{r\sin\varphi}{\sqrt{dx^2 + dy^2 + dz^2}} \\ \cos\theta &= \frac{dz}{d\ell} = \frac{r\tan\delta}{\sqrt{dx^2 + dy^2 + dz^2}} \end{aligned} \tag{168}$$

* The wheel itself was considered, however, as a two-dimensional case (wide cylinder).

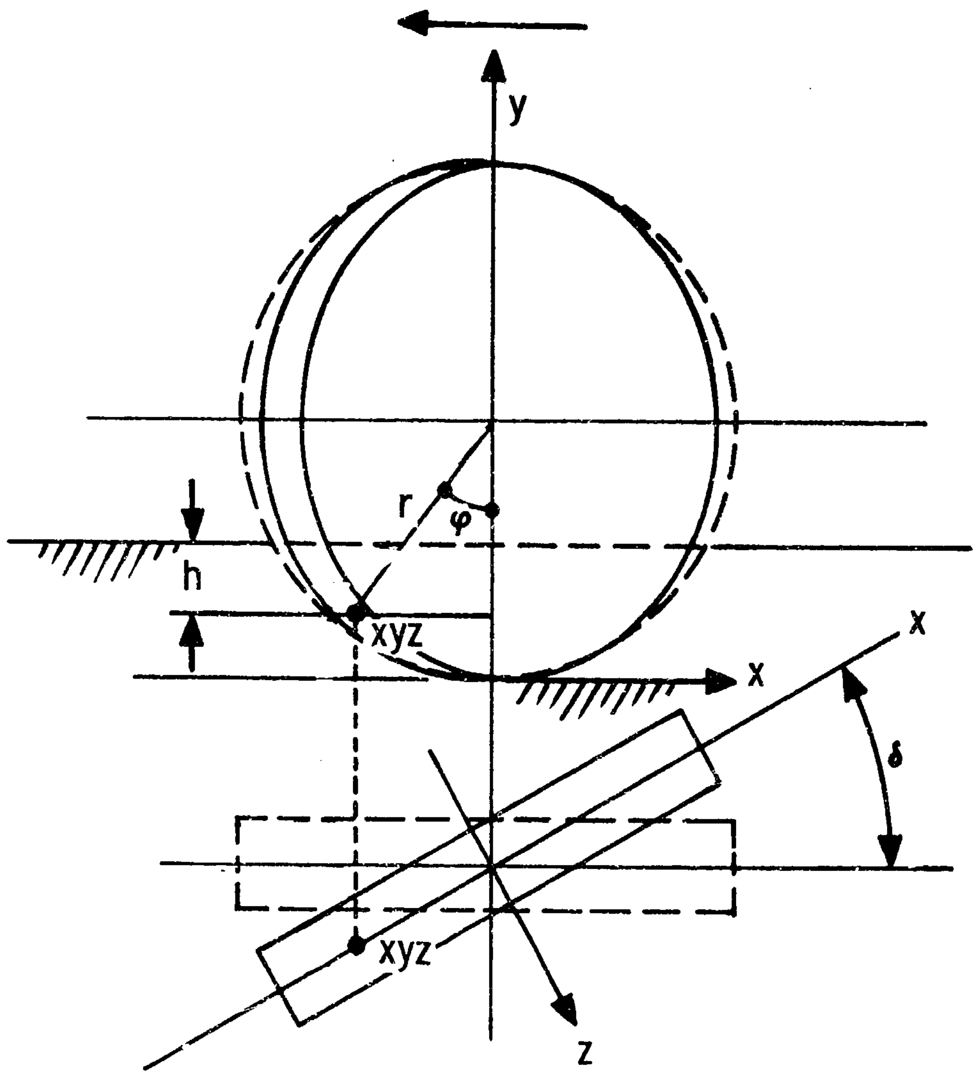


Figure 33 Simplified Krasilnikov's (1966) force-wheel geometry for a steering wheel at cornering angle δ .

where $d\ell$ is the length of the arc of the trajectory of point xyz equal to:

$$d\ell = \sqrt{dx^2 + dy^2 + dz^2} = \sqrt{r^2(1 + \tan^2 \delta) + r^2 = 2r^2 \cos \varphi} \tag{169}$$

Particles of soil which adhere to the rim move along the trajectories defined by equation (167), provided that pressure angles β and θ between the tangent to the trajectory at point xyz and the normal to the rim (compare Andreev's γ angles) do not exceed friction angle φ_s between the rim and the soil. Otherwise, soil particles will slide along the rim following trajectories "distorted" by φ_s = const. The reasoning was the same as that by Andreev, and the equations of "slide" trajectories were deduced in an elegant manner, by rotating the axes by φ.

This led again to the determination of horizontal and vertical forces acting upon the wheel, in much the same manner as before, assuming again that rim pressure obeyed Bernstein-Letoshnev's law along trajectory length, $p = k\ell$. Analysis of cornering forces followed, but experimental confirmation was only showing the right trend, although even this could not be verified because soil value k was not given. In general, progress was dim.

On this background it would be surprising not to find a Russian search for soil-wheel solution within visco-elastic soil properties. After all, everyone tried it. In particular, elegant solutions treating soil as a viscous fluid, produced by Kneschke (1957) or Wintergerst (1940), were conceptually very close to Maxwell's treatment of visco-elastic media, which was fully known to Russian scientists (see Bekker, 1956).

They also were familiar with the tutorial paper by Schiffman (1961) and with those written under the program of the Land Locomotion Laboratory in Detroit, which were read at the International Conference in Turin, Italy, in 1961.

Interestingly enough the first Russian study of wheel resistance in a visco-elastic medium was ascribed by Glagolev and Poletayev (1967) to Ishlinskii (1938). To what extent this was justified could not be ascertained because Ishlinski's reference is not available.

Glagolev and Poletayev were both PhD's (or equivalent) at Moscow Institute of Automotive Technology (Moskovskii Avtomechanicheskii Institut). Apparently, they did

not think too highly of the semi-empirical solutions by their agricultural colleagues since they did not quote them, referring instead to Maxwell and Reynolds, among a few other notables of the theory.

In their study they considered the "upper layer which consists of soil and organic matter;" they assumed that this layer of depth h (Figure 34) displays visco-elastic properties defined by Maxwell's model (see Bekker 1956):

$$\frac{\dot{\tau}}{G} + \frac{\tau}{\mu} = \dot{z} \tag{170}$$

where τ is stress; G is modulus of rigidity; μ is viscosity; and z is the strain. In the analysis of wheel problems, many simplifying assumptions were made:

- friction between the wheel and the soil is constant,
- and does not affect stress-strain distribution.
- The problem is two-dimensional,
- sinkage is very small: therefore,
- the arc of the rim in contact with soil may be replaced by the respective chord extended up to point A' (Figure 34).

The latter assumption led Glagolev and Poletayev to a very crude approximation of wheel sinkage z_y at point x:

$$z_y \cong \frac{b^2 - x^2}{2r} \tag{171}$$

which alone suggests that the solution of the problem must be biased with excessive error. The authors also dismissed the slip. Thus the speed of movement of any wheel point along x-x axis was: $v - (r + h_0)\,\omega$. Since h_0 was assumed small they further simplified even this equation by assuming that $v = r\omega$. Then the time during which the contact area BX acts upon the ground was:

$$t = \frac{b - x}{v} \tag{172}$$

Soil strain z(x) at point X was represented in dimentionless form:

$$z(x) = \frac{b^2 - x^2}{2rh} \tag{173}$$

Now, from Figure 34, equations of equilibrium of forces are:

$$\begin{aligned} -W + N &= 0 \\ F - S &= 0 \\ M + N\ell - Sr &= 0 \end{aligned} \tag{174}$$

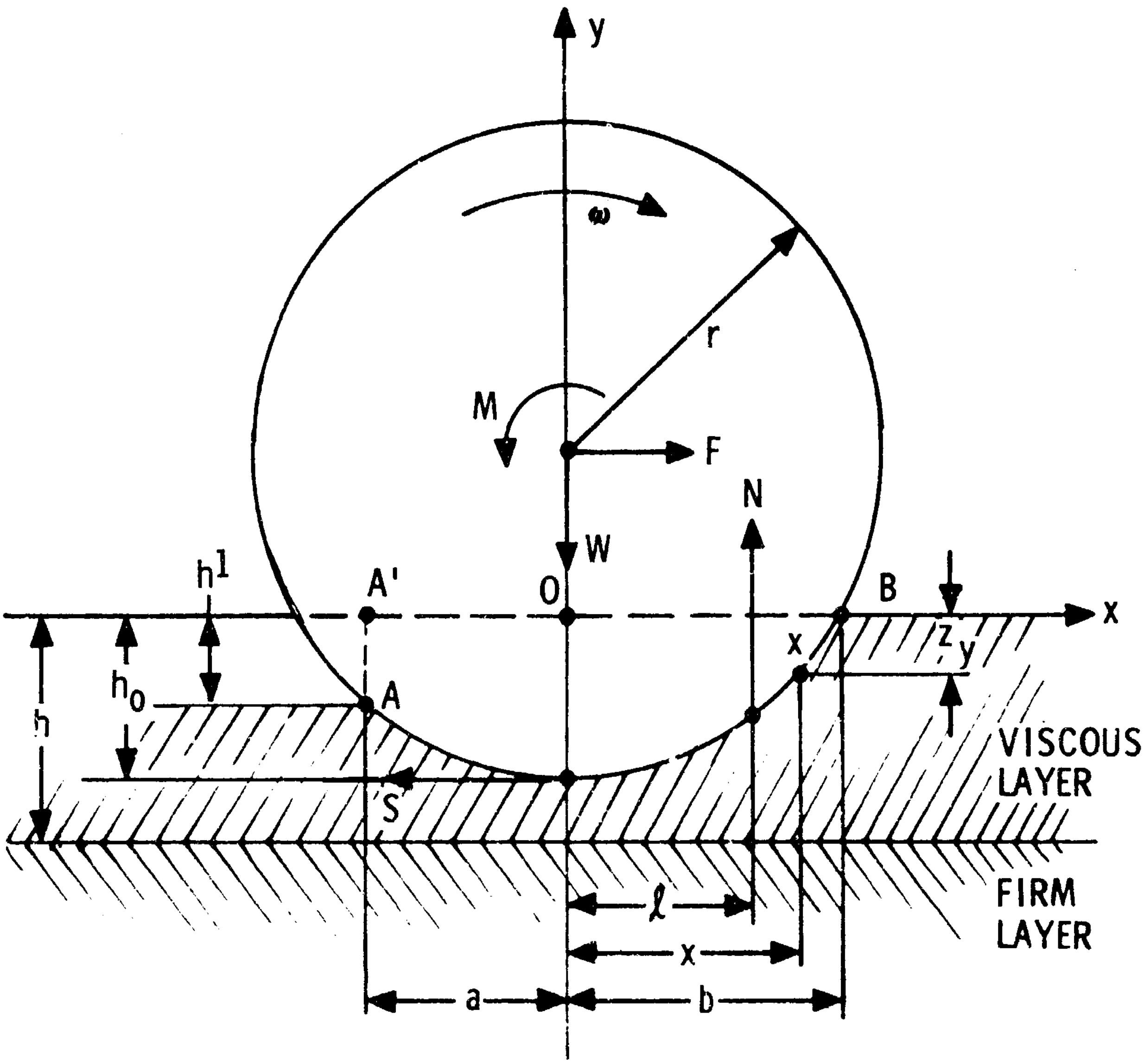


Figure 34 Glagolev and Poletayev's (1967) diagram of forces and wheel geometry, on a visco-elastic soil layer.

and,

$$N = W; \qquad S = F; \qquad F = \frac{W\ell + M}{r}$$

Integration of equation (170) gives:

$$\tau(t) = Gz(t) - \frac{G}{T}\int_0^t z(t')\, e^{-\left(\frac{t-t'}{T}\right)} dt'$$

(176)

and,

$$z(t) = \frac{\tau(t)}{G} - \frac{1}{GT}\int_0^t \tau(t')\, dt'$$

where, $T = \mu/G$ is the relaxation time. The stretch of soil, which enters into the contact with the wheel at $t = 0$, looses that contact at the time $t_1 = (a+b)/v$. The soil is then relieved of load; the final soil strain that remains upon wheel passage is:

$$z_f = \frac{1}{TG}\int_0^{t_1} \tau(t')\, dt' \qquad (177)$$

From equation (171) and from the speed of deformation v:

$$z(x) = \frac{b^2 - x^2}{2\,rh} = \frac{vt\,(2b - vt)}{2\,rh} \qquad (178)$$

and from equation (176)

$$\frac{2rh\,\tau(t)}{G} = v\,(2bt - vt^2) - \frac{v}{T}\int_0^t e^{-\left(\frac{t-t'}{T}\right)}(2bt' - vt')\, dt' \qquad (179)$$

or

$$\frac{rh\,\tau(\overline{OA'})}{vTG} = (b + vT)\left(1 - e^{-\left(\frac{b-x}{vT}\right)}\right) - (b - x) \qquad (180)$$

But the stress at point A is zero. Also OA' = -a; thus equation (180) gives:

$$(b + vT)\left(1 - e^{-\frac{b+a}{vT}}\right) - (b+a) = 0 \qquad (181)$$

Summation of normal stresses on distance -a and b (Figure 34) produces:

$$W = w\int_{-a}^{b} \tau(x)\, dx = \frac{vTGw}{rh}\left\{(b + vT)\left[(a + b) - vT\left(1 - e^{\frac{-b+a}{vT}}\right)\right] - \frac{(a+b)^2}{2}\right\} \qquad (182)$$

and from equations (182) and (181):

$$W = \frac{GwvT}{2\,rh} \,(b^2 - a^2) \tag{183}$$

where w is the width of the wheel. Depth of the rut of the wheel h' was determined from equation (177), considering strain z_f:

$$z_f = \frac{1}{TG} \int_b^{\frac{a+b}{v}} \tau\,(t')\,dt' = \frac{1}{TEv} \int_{-a}^{b} \tau\,(x)\,dx \tag{184}$$

and, considering the customary "coefficient" of rolling resistance (Figure 34)

$$z_f = \frac{W}{v\,\ell\,TG} \tag{185}$$

or, in combination with equation (183):

$$z_f = \frac{b^2 - a^2}{2rh} \tag{186}$$

Thus, sinkage h' :

$$h' = z_f h = \frac{b^2 - a^2}{2r} \tag{187}$$

In a similar manner, and in conjunction with equation (174), other forces, moments, and the "coefficient of rolling resistance ℓ " were defined.

It is suggested the reader draw his own conclusions as to the practicability of this method, and its reliability in prediction of wheel performance. In this respect the necessary field measurements of G and μ also should be considered.

The discussed example shows that the Russian approach tried everything the others have tried. The lack of any further information as to the use or even experimental verification of the Glagolev and Poletayev's method indicates that it met the same fate as that in the United States: it was forgotten in the profusion of impractical research. For, the additional amount of work which that method required because of additional idealizing assumptions could not compete for accuracy with less sophisticated methods that deal directly with hard empirical facts.

This lesson, however, even today is often overlooked by inexperienced researchers in ground mobility and by the leadership lacking a strategic concept of that research. A far more complex solution based on even less practical assumptions was, for example, recently attempted in this country with large expenditure of time and computer monies (Dagan and Tulin, 1968). And as expected, the authors asked in conclusion for more time and money, for "more and better experiments are necessary (they said) in order to validate the theory... (though) theoretical results were compared with some existing measurements and the agreement was generally satisfactory."

"Generally satisfactory" to whom? To the researcher? Maybe. But not to the engineer who wants to optimize wheel performance for a variety of terrain and mission variables, today – not in the unspecified future.

These words could have been spoken by a member of the Minsk School. Guskov of Minsk Institute of Technology, a contemporary to Glagolev and Poletayev, had worked long on the optimization of parameters of agricultural tractors, and in the book published on this subject (1966) by Mashinostroyenye (Machine Design) presented a very conservative solution for the rigid wheel.

It started, among others, with references to Goriachkin, Babkov, Katsygin, Bekker, and Söhne. Here the rigid wheel's force-geometry configuration was not much different from that by Letoshnev (1936). The fundamental change was the strong reaffirmation of the Russian soil value system based on hyperbolic functions. Thus, instead of the Bernstein-Letoshnev equation written in terms of rim path length ℓ:

$$p = k\ell^n$$

Guskov used Katsygin's equation (see Chapter II):

$$p = p_{KA} \tanh \frac{k_{KA}}{p_{KA}} \ell \tag{188}$$

If the elementary rim area is $dF = brd\alpha$ (Figure 35), then the normal elementary reaction to wheel rim, dN, is:

$$dN = pbrd\alpha \tag{189}$$

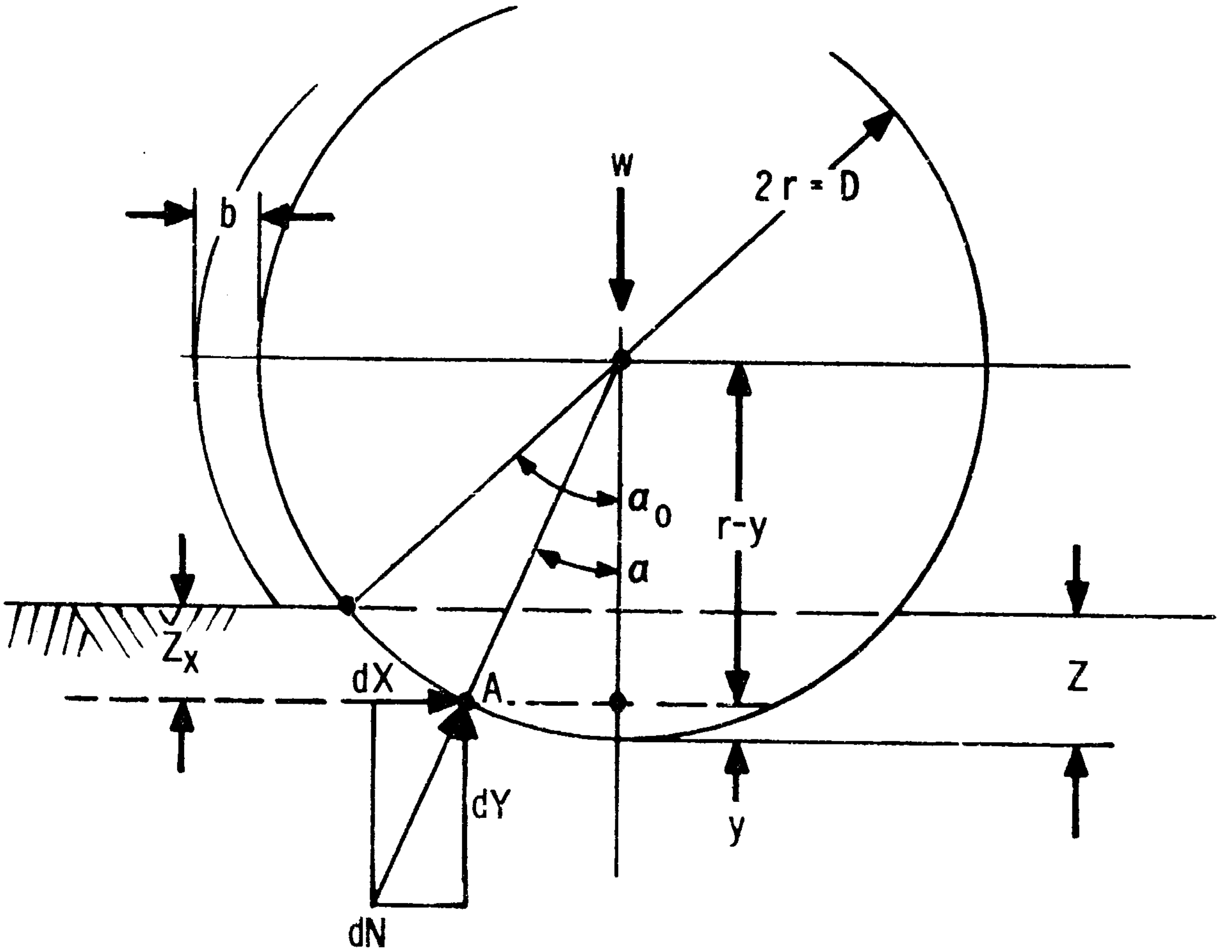


Figure 35 Guskov's (1966) Force-soil Deformation Plan for a Rigid Wheel

or if equation (199) is substituted:

$$dN = p_{KA}\, b\, r \tan h\, \frac{k_{KA}}{p_{KA}}\, \ell\, d\, \alpha \tag{190}$$

Since $r - y = r\cos\alpha$ (Figure 35), $dy = r\sin\alpha\, d\,\alpha$. But the length of the trajectory on which point A moved is ℓ ; hence $dy = d\,\ell \cos\alpha$ (compare Andreev, 1956), and $d\,\ell = r\tan\alpha d\alpha$. Accordingly the length ℓ of the path of point A is:

$$\ell = r \int_{\alpha}^{\alpha_o} \tan\alpha d\alpha = r\,\ell \left(\frac{\cos\alpha}{\cos\alpha_o}\right) \tag{191}$$

Substitution equation (191) in equation (190) and integrating by substitution, and then developing the result into series and taking only the first number of the series, Guskov obtained wheel load W as follows:

$$W = \int_{\alpha}^{\alpha_o} br\cos\alpha p_{KA} \tanh\left[\frac{k_{KA}}{p_{KA}} r\,\ell_n\, \frac{\cos\alpha}{\cos\alpha_o}\right] d\alpha \simeq k_{KA} br^2(\tan\alpha_o - \sin\alpha_o) \tag{192}$$

However, $\tan\alpha_o = \sqrt{zr}/(r-z)$ and $\sin\alpha\sqrt{2zr}/(r-z)$. Hence equation (192) was transformed in this form:

$$W = k_{KA}\, bz\sqrt{2zr}\,(\frac{r}{r-z}) \cong k_{KA}\, bz\sqrt{2zr} \tag{193}$$

from which

$$z = \sqrt[3]{\frac{W^2}{k_{KA} b^2 D}} \tag{194}$$

Obviously equations (193) and (194) are equivalent to Bernstein-Letoshnev-Bekker equations (see Bekker, 1956) which were deduced in the early thirties and fifties with a much lesser mathematical manipulation, merely assuming that $p = kz^{n=1}$; Guskov's using hyperbolic function and then simplifying the result could not have given results different from these earlier solutions. The same new complexity and yet the same old solutions were involved in determining motion resistance R (Figure 35):

$$dR = dN\sin\alpha \tag{195}$$

and,

$$R = \int_{\alpha}^{\alpha_o} br \sin \alpha p_{KA} \tanh \left[\frac{k_{KA}}{p_{KA}} r \ln \frac{\cos \alpha}{\cos \alpha_o} \right] d\alpha \cong k_{KA} br^2 \frac{(1-\cos \alpha_o)^2}{1 + \cos \alpha_o} \tag{196}$$

since $\cos \alpha_o = (r-z)/r$:

$$R = k_{KA} \; br \; \frac{z^2}{2r - z} \simeq \frac{1}{2} \; k_{KA} \; bz^2 \tag{197}$$

This again is nothing more than the Bernstein-Letoshnev-Bekker equation for motion resistance of the rigid wheel, at $p = kz^{n=1}$ or $p = [(k_c/b) + k_\phi] \, z^n$ (compare Bekker, 1956, 1960).

Why Guskov chose in 1966 to "generalize" the solution with Katsygin's hyperbolic function, and then to simplify the computations in order to arrive at a simple solution which could have been developed by Letoshnev in 1936, can be explained by his desire to move that "tanh-solution" may be reduced to the old solution. The chance to speculate in this respect was augmented by Guskov's own statement to the effect that he developed:

> "the hyperbolic tangent into a series and chose only the first member of the series... (For) the error at the existing wheel loads and wheel sinkages is no greater than 3%."

Why then did he not use the Bernstein-Letoshnev-Bekker method?

Work on tracked tractor performance by Katsygin and Guskov (1968) continued the same line of thought, as will be discussed in the chapter on tracks. However, this time the authors did not resort to over-simplified integration of hyperbolic functions, but implied the use of analog computers. If the cost involved was worth eliminating the 3% error that would occur if they used the simpler Bernstein-Letoshnev approach, it was not discussed. The present author believes that the answer is no unless the same computer program was used very often. This could happen only if frequent system analyses were performed.

Another reference by Guskov (1968) to the digital computer "Promin" used in a parametric evaluation of tractors, based again on hyperbolic tangent functions, seems to indicate that at least the Central Institute of Agricultural Machinery has embarked upon parametric evaluations of wheel-soil systems, using Katsygin's soil values when computers became available.

Surprisingly, however, the book by automotive engineers Vasiliev, Dokuchayeva, and Utkin - Linbovtsov (1969) published by Moscow's Mashinostroyenye (Machine Design) reviewed the theory of locomotion as developed by Letoshnev (1936) and Bekker (1960). The authors performed very extensive tests and concluded:

> "these (tests) have shown that it is advisible to use Bekker's equations. His formulae are simpler and appear to be more general than the others, for instance, equations by V. V. Katsygin..."

Thus there exists an evident difference of opinion between the Minsk School and the Automotive School as represented by the Scientific Technical Automobile Institute (NATI), Moscow Automotive and Motor Institute (MAMI), and the Federal Institute for Mechanization (VI Me).

What is at stake in this difference of opinion among the two Russian Schools? What is at stake in similar differences among the American researchers? A detailed answer to this question requires a separate study. Such a study was partially performed by Schuring (1968) who has clearly shown what the real issue is. In his classic dissertation, which commanded expertise and imagination, he analyzed the predictive merits of various wheel theories proposed by a number of authors between 1913 and 1968. The present author added theories of Letoshnev and Margolin, and Guskov's wheel theory (the latter based on the simplified Katsygin soil value system). The results are shown in Table 21 in terms of unit motion resistance f versus ratio z/r of wheel sinkage z to wheel radius r.

Two types of soil were considered: $n = 1$ (sand) and $n = 0$ (soft plas , clay). The value of f equal to R/W was calculated from formulae presented by various researchers, at various times. The references were ordered chronologically. Solutions that did not yield themselves to an explicit formulation in terms of a constant and z/r ratio were not discussed (Andreev, 1956; Janosi, 1963; Sitkei, 1966). Solutions by Matsepuro and Yanushkevich (1961) (including slip by Vernikov (1940)) and Glagalev and Poletayev (1967) (including speed) could not be compared directly; some of them fall in the same category as those by Gutyar (1955) and Schuring (1968), i.e., consider the partial recovery of ground deformation after the wheel passage. In Table 21 such recovery was assumed to be negligible, which corresponds to rigid wheels at sinkage that has a real significance. Gutyar's solution was not included. The merits of the other solutions were discussed in the preceding pages.

Table 21

Researcher	Soil		Remarks
	Sand	Plastic Clay	
Bernstein (1913)	$f = 0.60\sqrt{z/r}$		$n = 0.5$
Letoshnev (1936)	$f = 0.52\sqrt{z/r}$	$f = 0.69\sqrt{z/r}$	
Gruzdev (1944)	$f = 0.53\sqrt{z/r}$		Corresponds to $n = 1$
Garbari (1948)	$f = 0.53\sqrt{z/r}$		Corresponds to $n = 1$
Bekker (1956, 1960)	$f = 0.53\sqrt{z/r}$	$f = 0.71\sqrt{z/r}$	
Uffelman (1961)	n/a	$f = 0.71\sqrt{z/r}$	
Margolin (1961)	$f = 0.69\sqrt{z/r}$	$f = 1.02\sqrt{z/r}$	Methodological origin unknown
Guskov (1966)	$f = 0.53\sqrt{z/r}$	$f = 0.71\sqrt{z/r}$	For simplified Katsygin solutions
McRae (1967)	$f = 0.71\sqrt{z/r}$		
Schuring (1968)	$f = 0.71\sqrt{z/r}$		

Table 21 shows that in spite of the variety of approaches between 1913 and 1968 all the equations regarding motion resistance of a rigid wheel have practically the same predictive power. As Schuring (1968) observed, for non-rebounding soils at practically significant sinkages, " the maximum deviation from the average coefficient of rolling resistance

$$f = 0.62\sqrt{z/r}$$

is not more than ± 15%. This remark does not consider the Margolin formula which slightly increases the deviation.

But what are the deviations in soil properties even in the same area? What are the changes in n-values due to meteorological conditions? Experience indicates that they may be, and most frequently are, so great as to make the ± 15% variation band totally insignificant. What good is it then to make a more accurate equation? Table 21

indicates that for practical purposes the attainable level of predictive accuracy of rigid wheel formulae has been reached; it is unlikely that future research could increase that accuracy at a reasonable cost.

It seems that top Russian researchers realize this. If they cultivate the divergency of opinion between the automotive and agricultural engineers, their disagreement is tempered by the agreement in a basic school of thought. We certainly should try to avoid our costly controversies, for the prize is not worth the effort, particularly where the school of thought is lacking. This does not imply that no more research is needed. It simply means that first a professional research strategy should be established in order to avoid the pitfalls when trying to reach more accuracy at an exorbitant cost, where it does little good (Bekker, 1969).

Pneumatic Tires

Pneumatic tires for off-road locomotion appeared much later than the rigid wheels. In addition, the engineers were more preoccupied with tire life than with the mathematics of its performance in soft soils. For this reason tire theories appeared late.

Thus, Avtotraktornyi Spravochnik (edited by Kristi, 1938) was concerned only with the rigid wheel, even without considering soil properties as such. Application of pneumatic tires was only sketchily mentioned. The United States was the first to foster some sort of a systematic tire testing (McKibben et al., 1939, 1940).

The U.S.S.R. was late. Although tests were performed before World War II the first recognition of a need for the tire theory appeared in 1948, as far as could be ascertained from the Editors' note published in Siel'khozmashina (Agricultural Machinery):

> "the problem of rational use of pneumatic tires with agricultural machinery now appears to be timely. Material published (in this magazine) gives the designer a method of calculation of tire performance in various conditions of agriculture, and shows for which kind of equipment pneumatic tires are economical and technically sound. The Editors request the designers, specialists, and scientific workers for contributions to be published in this magazine."

This invitation followed a theoretical article by Omelianov (1948) of the Federal R&D Institute for Agricultural Machinery (VISHOM).

Numerous experiments performed by VISHOM with pneumatic tires since 1935 led Omelyanov to the proposal of what appears to be the first tire theory. The brief outline of the theory is as follows.

Resultant $\bar{V}$ of vertical reactions of a hard road is located at distance, a, from wheel axis, in the direction of motion, thus creating a moment of resistance (Figure 36). This moment is overcome by pulling force P and the frictional forces ΣS between the tire and the road. Omelianov assumed that the motion resistance R, or its equivalent pulling force P, is expressed on a hard ground by the function:

$$P = f\,(W_p\, b\, D\, m_t) \tag{198}$$

where m_t depends on tire structure. In order to determine that function for a given tire the author applied dimensional analysis:

$$P = f(W\ p\ D) = \text{const}\ W^{\alpha}\, p^{\beta}\, D^{\gamma} \tag{199}$$

or, dimensionally:

$$(kg)^1 = (kg)^{\alpha}\,(kg/cm^2)^{\beta}\ (cm)^{\gamma} \tag{200}$$

Hence:

$$\begin{aligned} \alpha + \beta &= 1 \\ \gamma - 2\beta &= 0 \end{aligned} \tag{201}$$

Solution of two equations (201) with three unknowns required experimental determination of one of them. VISHOM found statistically that α varies between 1.15 and 1.57, and that the mean was $\alpha = 4/3$. Thus from equations (201) $\beta = -1/3$, and $\gamma = -2/3$. Hence:

$$R^1 = P = C_2\ \sqrt[3]{W^4/p\,D^2} \tag{202}$$

where C_2 is the constant of equation (199).

Experiments with various tires gave the following values for C_2:

Table 22

Tires	No. of Ply	C_2
6.50 - 20	6	0.054 to 0.072
6.00 - 16	4	0.055 to 0.080
7.50 - 28	6	0.064 to 0.076

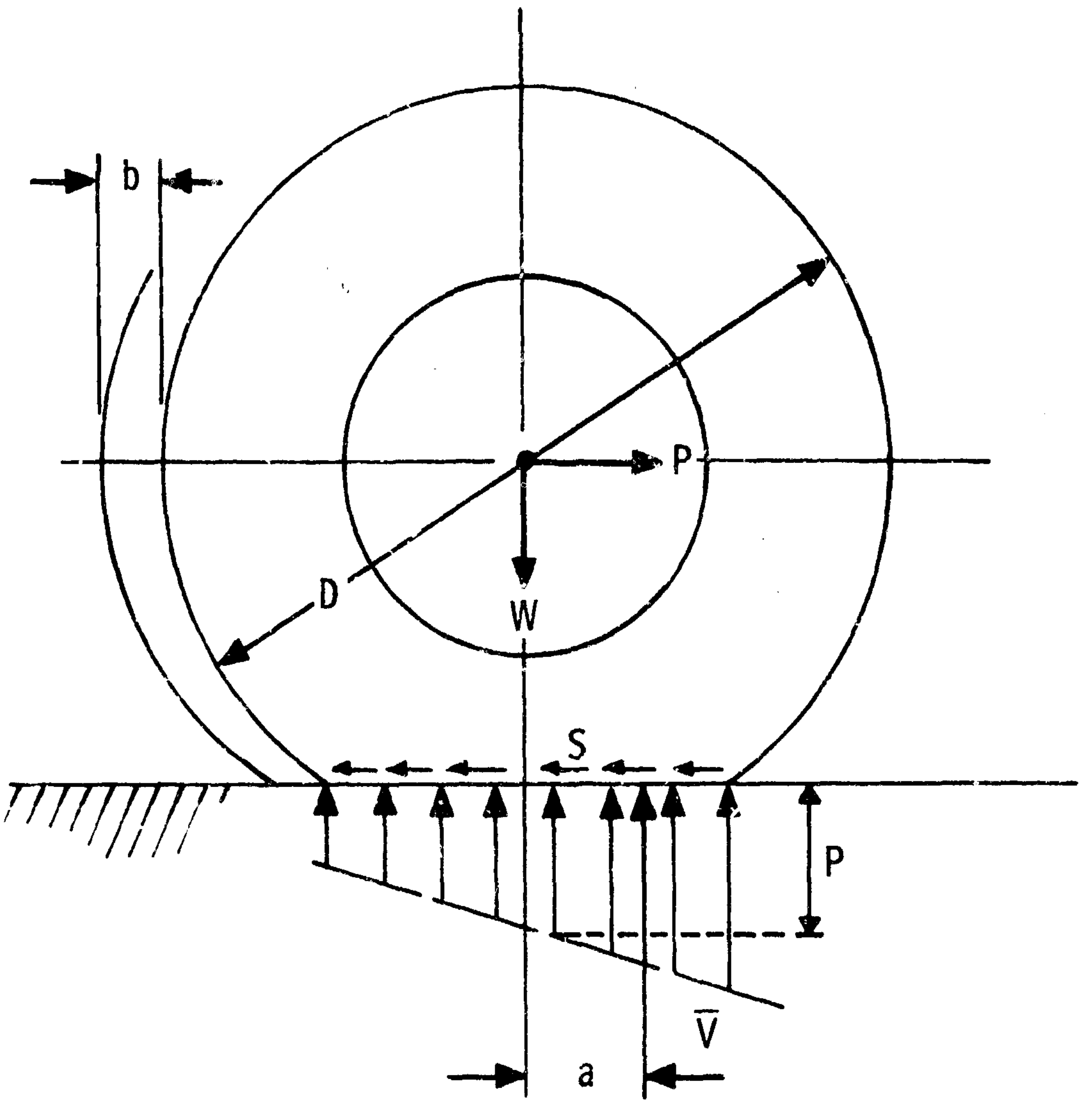


Figure 36 Omelianov's (1948) Force-deformation Plan for a Pneumatic Tire

As mentioned before, equation (202) applies to hard ground. In order to determine motion resistance of rut making in soft ground, Omelianov performed tests in a sand bin. These showed that for a given wheel and soil:

$$R'' = \text{const. } W^{\alpha}$$

$$R'' = \text{const. } p^{\beta}$$

and that $\alpha = 1$, and $\beta = 1/3$.

Next he assumed that besides the tire properties, Bernstein-Letoshnev ground properties $k(kg/cm^3)$ also enter into the picture. Accordingly, soft ground motion resistance R'' was expressed as:

$$R'' = f(W\,p\,k\,D) = \text{const } (W^{\alpha}\,p^{\beta}\,k^{\gamma}\,D^{\delta}) \tag{203}$$

and,

$$\begin{aligned} \alpha + \beta + \gamma &= 1 \\ -2\beta - 3\gamma + \delta &= 0 \end{aligned} \tag{204}$$

With experimental values of $\alpha = 1$ and $\beta = 1/3$, other exponents were determined from equation (204): $\gamma = -1/3$ and $\delta = -1/3$. After denoting the constant in equation (203) by C_1, Omelianov finally obtained:

$$R'' = C_1\,W\,\sqrt[3]{p/kD} \tag{205}$$

The value of coefficient C_1 was not given. Instead Omelianov produced empirical coefficients of motion resistance $f = R'/W$ for stubble and the 7.50 - 20 tire, assuming that $f = C_1\,\sqrt[3]{p/kD}$:

Table 23

f	W
0.067 to 0.100	400 kg
0.054 to 0.095	700
0.068 to 0.096	1000

A short analysis of a driven wheel followed Omelianov's theory. The larger f-values corresponded to higher inflation pressures p, which were varied within 1 to 3 atmospheres.

The inadequacy of Omelianov's theory was obvious: its weakness lay in the "constants" C_1 and C_2, which are not constant at all but dependent on numerous parameters of soil-tire system.

On the other hand, if simple empirics developed at the same time in the United States by McKibben and his followers is considered, then Omelianov's work emerges as a first rational, though primitive, approach to tire analysis.

It is interesting to note that Omelianov's theory was the only one as far as it could be ascertained, which was started with dimensional analysis. The contemporary work in the United States by Nuttall (see, Chapter XI in the reference by Bekker, 1956) went much further and deeper in that respect, though it was originally concerned with a rigid wheel only. The Russians thus far did not use dimensional analysis in wheel research, which will be discussed later.

Collective work on automobile theory published sometime after 1948 (exact information is lacking since only an incomplete copy of the book is available) was concerned with tire hysteresis, but assumed the force scheme shown in Figure 36 and the rolling resistance moment $\overline{V}$ a.

The same work in a chapter on tractor theory was concerned with rigid wheels and Bernstein-Letoshnev theory. This indicates further that Omelianov's was the first to attempt theorizing on tires.

As in America the Russian Automotive engineers preferred testing to theorizing. For example Briuhovets (1957) described a laboratory and field experiment which Waterways Experiment Station (WES) ran in a laboratory almost a decade later (Powell and Green, 1965). A typical read-out of his experiments was shown below:

Tire Load	Infl. Press.	Deformation		Tire Def. on Concrete	Rolling Road		Motion Resistance	Slip, Efficiency	Soil Penetration Pressure	Soil Moisture Content
		Tire	Soil		Stat.	Dyn.				

These tests led to the recommendation for changing standard field test procedures GOST 7057-54. The experiments involved no theory but reached a practical goal in establishing techniques for field testing. What WES experiments have achieved is unknown to this writer.

A similar approach to the same problem was made later by Vasilevich (1959), though he used a more sophisticated mathematical apparatus for evaluation of experimental data. Omelianov was not quoted. Bernstein was referred to under the disguise of "Goriachkin formula," Both Lvov of Russia (1952) and Heyde of East Germany (1957), who did not contribute anything to tire theory, also were quoted for courtesy reasons, it seems.

This state of affairs may be partially understood when realizing that the tire itself was little known, from an applied mechanics viewpoint. As a result Poletaev and Kolobov (1959) complained in an agricultural magazine that

> "thus far there are no accurate analytical methods for determination of load carrying capacity of tires,"

and proceeded with more experiments. But Ageikin (1959) of the Automotive Research Institute (NATI) was the first who decided that the time had come for the development of more generalized analytical expressions which would encompass all the important soil-tire parameters. To this end he experimented with thin-walled tires (no tread) and established the following points:

- tire flattens in mid-portion of the ground contact area;
- for optimum inflation pressure, tire profile widens in ground contact area, 20 to 30%;
- mean pressure in the flattened portion of the tire depends little on soil properties, and is primarily defined by tire properties:

  $$p = p_{infl}\, C_3 + p'_c$$

  where $C_3 \cong 0.9$ to 1.0, and $p'_c = 0.4$ to 0.7 (see equation 34).
- ground pressure in the curved portions of the tire depends on the depth of sinkage, following Letoshnev's equation: $p = kz^n$.

  This equation also is applicable to high pressure tires, when no flattening of the ground contact area occurred.

On the basis of these assumptions Ageikin proposed the following solution. Equilibrium between tire load W and ground pressure p acting upon the flattened quasi-eliptical

ground contact areas as shown in the shaded surfaces in Figure 37 may be expressed by equation:

$$W = \frac{\pi}{4} p [\ell b + 0.4 \varphi (LB - \ell b)] \tag{208}$$

The symbols were explained either on the drawing or in the symbol index. Coefficient φ is a ratio of p to the average pressure of the curved zones of the tire. This value was reproduced after Ageikin on Figure 38 in terms of $2z/(r + r')$, where r' is the radius of the tire side under load (compare Rotta in Bekker, 1956).

In equation (208), it was assumed for the sake of simplicity that the ground contact areas are elliptical segments. Sinkage z was defined from equations (207) and Bernsteinian $p = kz^n$:

$$z = \left[\frac{\bar{p}}{k}\right]^{1/n} = \left[\frac{p_i C_3 + p'_c}{k}\right]^{1/n} \tag{209}$$

which is identical to Bekker's equation independently developed at the same time (Bekker, 1960).

The width of the flat ground contact area b and radius r' change as a function of radial deformation Δ (see Rotta in Bekker, 1956, and Figure 37):

$$\begin{aligned} h &= \Delta + r' (1 + \cos \gamma) \\ B_F &= b + 2r' \sin \gamma \\ U &= b + 2r' (\pi - \gamma) \end{aligned} \tag{210}$$

where U is the perimeter of the tire profile, which was assumed constant since the tire does not stretch much under the load. Width of the curved ground contact area, for $z \angle r'$ was expressed by equation (Figure 37):

$$B = b + 2\sqrt{2 r'z - z^2} \tag{211}$$

and for $z > r'$

$$B = b + 2r' \tag{212}$$

Length of the ground contact area for the flat and curved tire portions may be derined also from Figure 37:

$$\ell = 2 \sqrt{2r \Delta - \Delta^2} \tag{213}$$

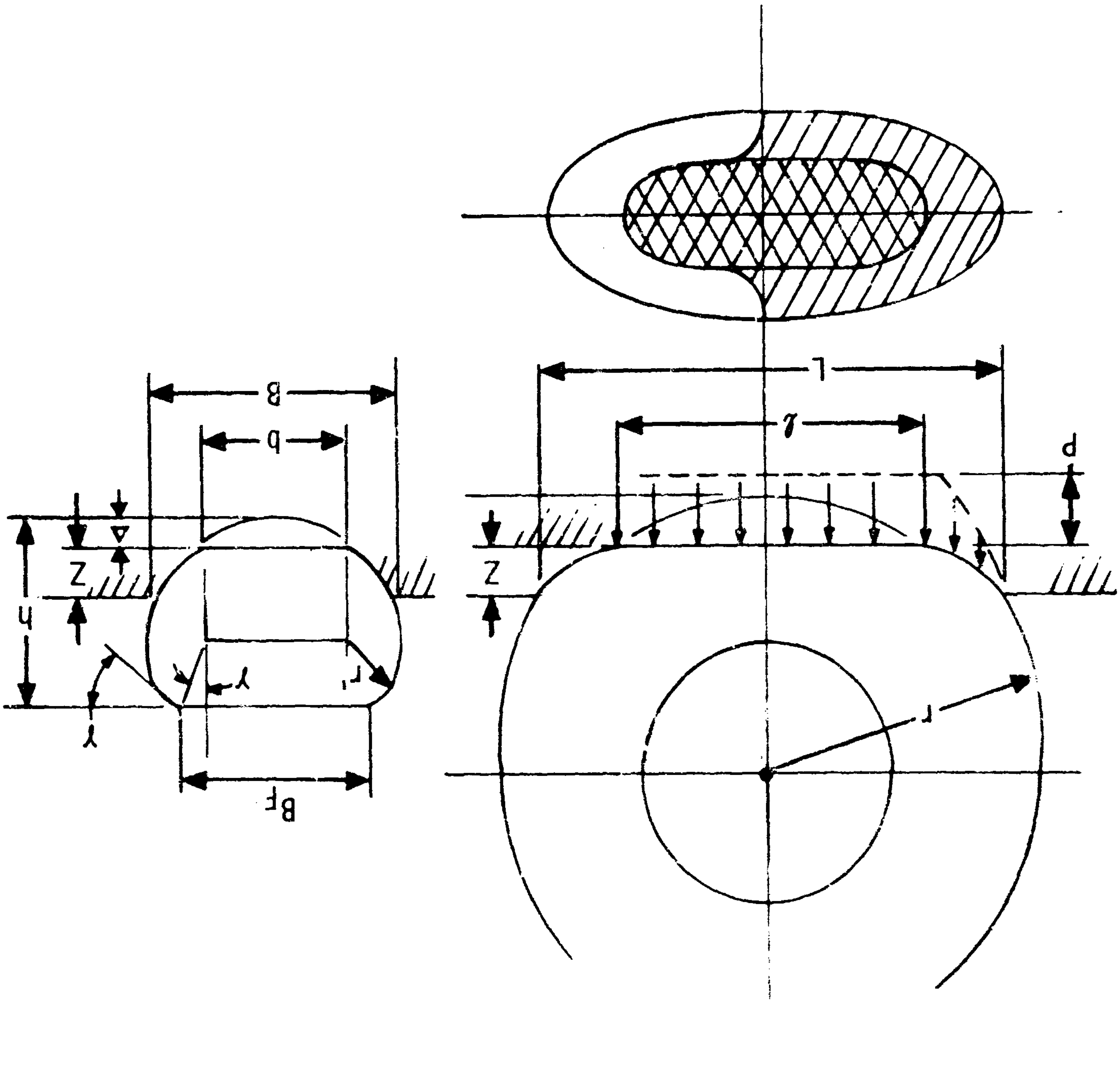


Figure 37 Ageikin's (1959) Load Deformation Plan
For a Pneumatic Tire

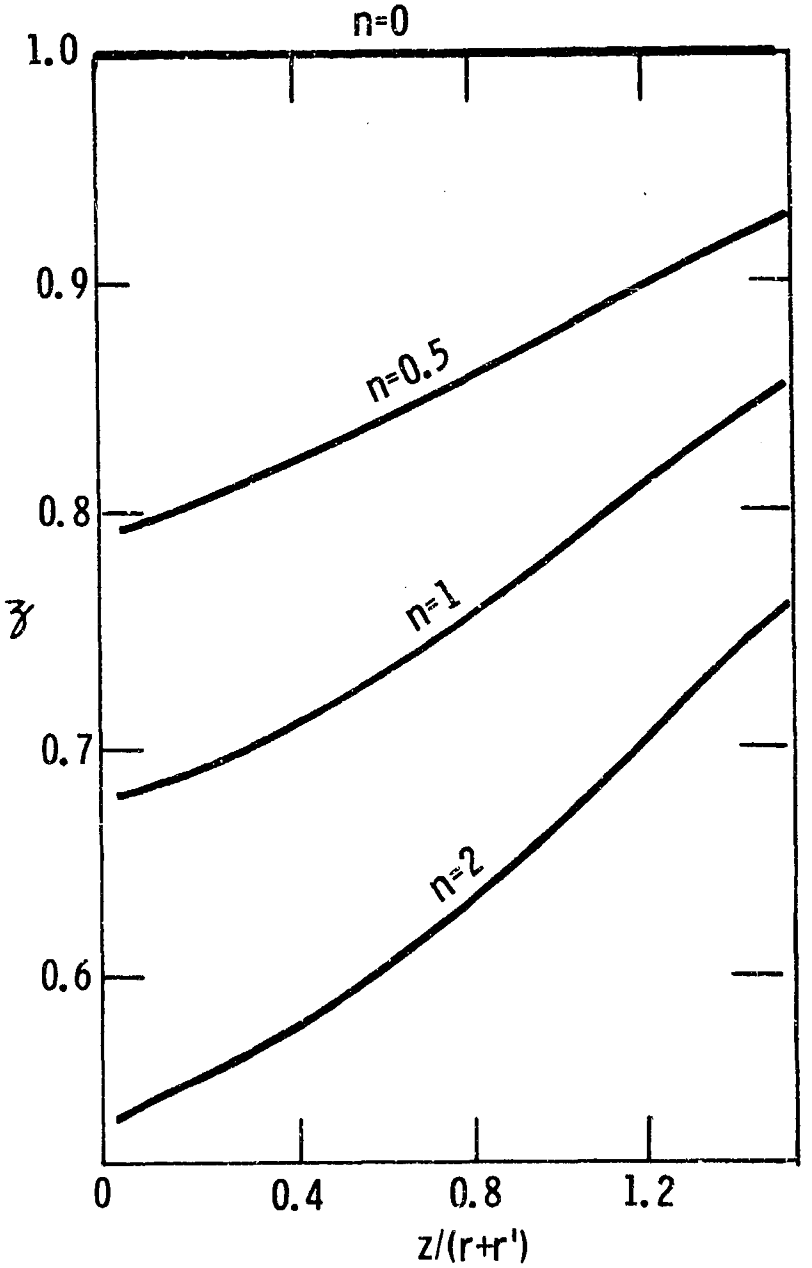


Figure 38 Relation Between Coefficient ζ and the Ration z/r + r' (Ageikin, 1959)

$$L = 2\sqrt{2r(z + \Delta) - (z + \Delta)^2} \qquad (214)$$

When determining radial deformation Δ of the tire, and the ground contact area, as a function of load and ground deformation z, Ageikin recommended the following steps:

- determine z from equation (209);
- assuming Δ and solving equations (210), determine b and r';
- solving equations (211), (213), (214), and (208), define B, L, ℓ, and W;
- upon determining W for the assumed Δ's, plot relationship $\Delta = f(W)$ and find Δ, which corresponds to the postulated wheel load W_p;
- reiterate the process and find b, ℓ, B, and L for W_p.

Figure 39 shows in solid lines the experimental relationship between Δ and p_i, and the calculated one – in interrupted lines. The method apparently is quite satisfactory in the investigation of the tire with deflection larger than 8% for any ground which can be defined with equation $p = kz^n$. Note that case (d) refers to a two-layer soil which does not yield itself directly to the investigation of means of $p = kz^n$ equation (Bekker, 1969). Apparently Ageikin used some sort of extrapolation which, however, was not specified.

Figure 40 shows analysis of tire behavior for various unloaded tire diameters D and profile width B'. Interestingly enough, Agekin's 1959 article was only concerned with tire and rut geometry. It appears to have been the first part of a work which later continued along the previously discussed lines.

The second article by Ageikin (1960) was preceded by Bekker's (1960) publication of tire theory, and reflected the same basic thought, but was broadened by the treatment of a complete vehicle instead of a single tire. Some additional empirical refinements are worth attention and lead to better results than those achieved in the U.S.

Although Ageikin did not refer to the book by Bekker, not only his basic assumptions but also the denotation of slip deformation by the letter "j" appears to have been borrowed from the American work. The j-denotation appears to be particularly a

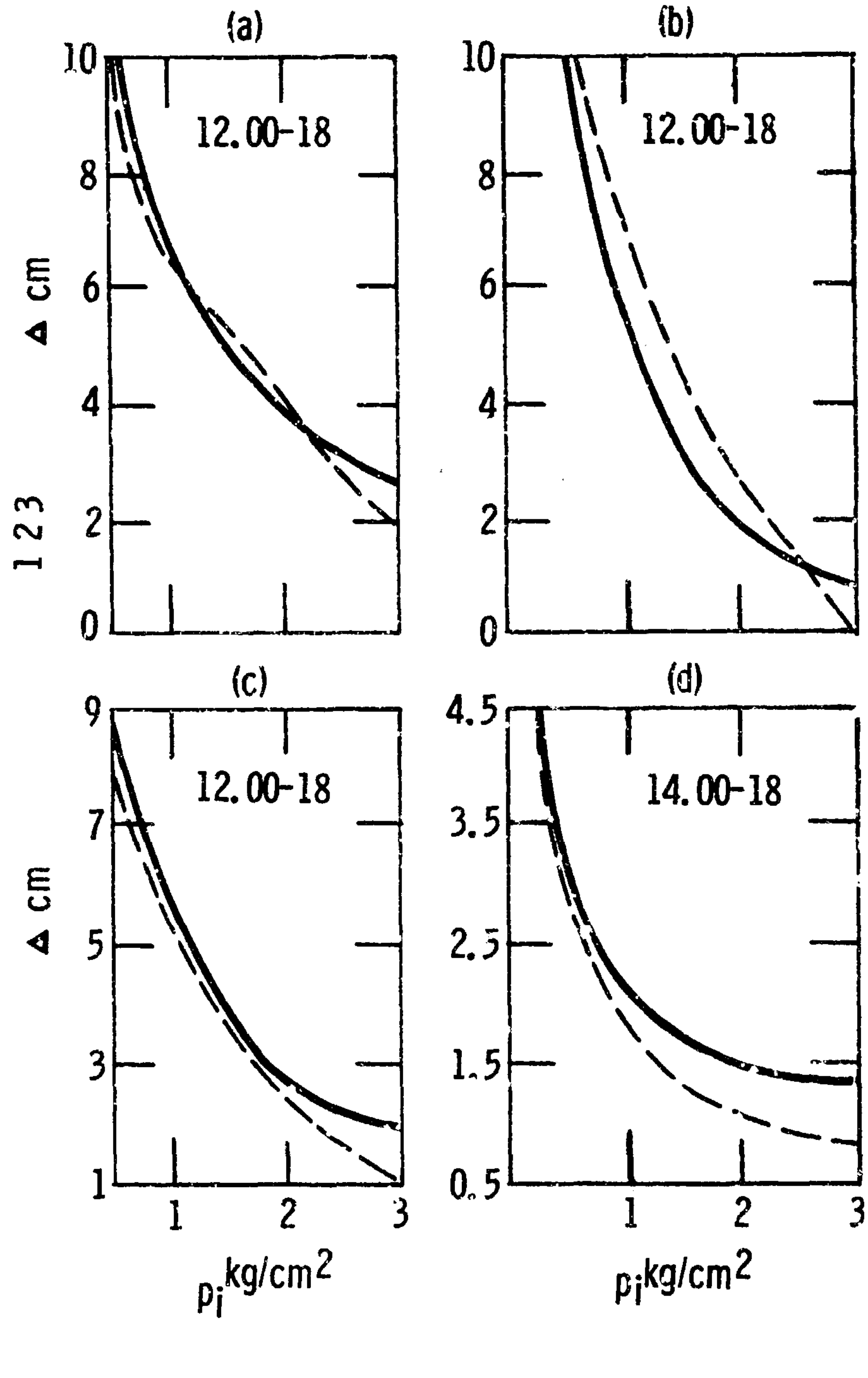
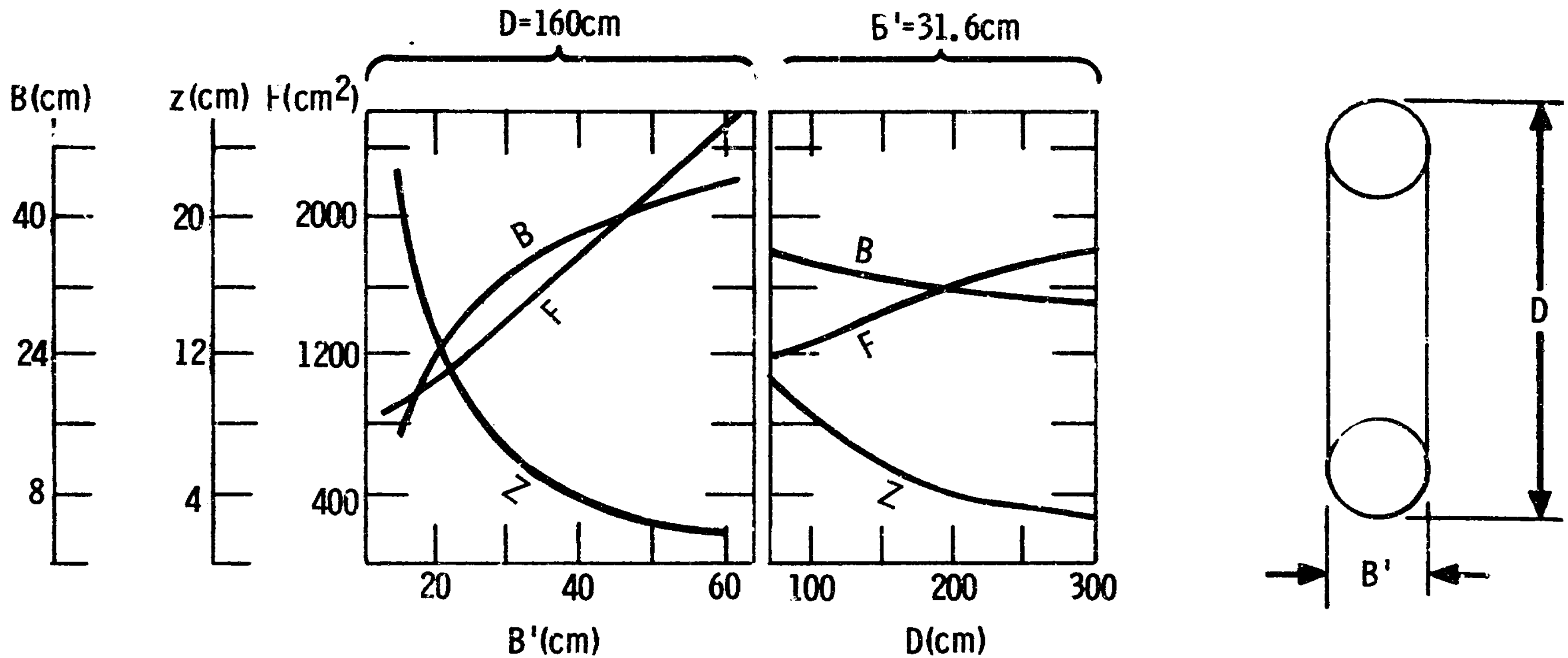


Figure 39 Experimental and theoretical relationship between tire deflection Δ and inflation pressure p_i after Ageikin (1959) for 12.00 - 18 and 14.00 - 18 tires.

(a) dry sand; n = 1; k = 0.52; W = 1520 kg
(b) Chernozem field: n = 0.5; k ≃ 1; W = 1520 kg
(c) wet, stirred sand: n = 1.5; k= 0.075; W = 1500 kg
(d) wet, heavy loam: n = 0; k = 0.64 to depth of 9.5 cm, and n = 1; k = 0.44 at depth below 9.5 cm; W = 1000 kg.



WET SAND: n=0.5; k=0.5; W=1500 kg; Δ/B'=0.2

Figure 40 Ground Contact Areas F, Rut Width Band Sinkage z of Times Calculated as a Function of Tire Diameter D and Profile Width B (Ageikin, 1959)

strong proof of American influence, because the Russian engineers always used their own symbols, most often written in the Cyrillic or Greek letters. Hence, only an extraordinary coincidence would define the shear deformation in a Russian text by the same letter of the latin alphabet as that used in an American book.* Ageikin's definition of the drawbar pull and motion resistance of the tire further indicates his close following of progress in the U. S. A. The main theme this time was the selection of inflation pressure for tires with adjustable pressure.

Again tire bearing capacity was determined as shown in equation (208) and Figure 37. Equation $p = kz^n$ was incorporated at the outset. Surprisingly, coefficients 0.5 and 0.4 instead of 0.6 and 0.4 were used,** apparently as a result of new experimental evidence:

$$W = \frac{\pi}{4} kz^n [\, \ell b\,(1 - 0.5\gamma) + 0.4\ LB\,] \tag{215}$$

No explanation for this change was given. Equation (215) refers to a single tire. For an N-wheel vehicle weighing W_n and having an even axle load distribution:

$$W_n = (N\,\pi/4)\ kz^n [\, \ell b\ (1 - 0.5\gamma) + 0.4\gamma\ LB\,] + k(z - h_g)^n\ \delta_F A' \tag{216}$$

where h_g is ground clearance of the part of vehicle body interfering with the ground. A' is the size of the interfering part and δ_F is the form coefficient of that part, which in case of a rectangle equals a unit.

To determine soil thrust H, Coulomb's formula was used for the first time in the Russian tire studies, as far as could be ascertained:

$$\tau_{max} \cong c + p \tan \varphi \tag{217}$$

and the triangular or quasi-triangular shear stress distribution was assumed by Ageikin in conformity with Bekker (1956) and Söhne (1956).

* Kristi (1936) used to denote slip deformation by a multiple of Δ.

** Transformation of equations (208) and (215) gives, respectively, $W = (\pi_p/4)\,[0.6\ z\ell b + 0.4\ z\ LB\,]$ and $W = (\pi p/4)\,[0.5\ z\ \ell b + 0.4\ z\ LB\,]$

The geometry of the ground contact area was defined as in equations (211), (213), (214), and in abbreviation (Figures 37 and 40), it was denoted by:

$$b = \alpha_1 B' \qquad r' = \alpha_2 B' \tag{218}$$

where α_1 and α_2 are manufacturer's tire coefficients which at 35% of maximum tire deflection are $\alpha_1 = 0.79$ and $\alpha_2 = 0.228$.

The order of solving the equations was recommended by Ageikin as follows:

- determine ℓ, b, r' from equations (123) and (218);
- for a certain number of assumed values of z, determine L and B from equations (211) and (214). A' has to be assumed in accordance with vehicle design data. Then, W_n may be determined from equation (216):
- construe graph $z = f(W_n)$, and
- for admissible sinkage z, select proper L, B.

Motion resistance R of the vehicle is composed of two parts: 1) drag R_a produced by the axles if $z > h_g$, and 2) drag due to rutmaking R_c. Then:

$$R = R_a + R_c \tag{219}$$

The expression for R_a was proposed by Ageikin in the following form:

$$R_a = \gamma_1 k (z - h_g)^n \left[\frac{(z - h_g) B_1}{n+1} + A' \mu_r \right] \tag{220}$$

where γ_1 is a coefficient of form of the lower part of the vehicle body. B_1 is the width of the swath produced by the lower part of the vehicle body, in the ground.

For the vehicles GAZ-63 and ZIL-157 the values of δ_F and γ_1 were given in Table 24:

Table 24

n	δ_F	γ_1
0	1.00	0.75
0.5	0.85	0.65
1.0	0.75	0.60
1.5	0.68	0.55
2.0	0.62	0.50

Soil compaction drag was expressed by equation:

$$R_c = \frac{k}{n+1} [\gamma_2 z]^{n+1} [b + \gamma_3 (B' - b)] \tag{221}$$

where γ_3 is a coefficient of curvature of side walls of the tire as shown in Figure 41. γ_2 is a parameter which involves the deviation of ground deformation from the vertical compaction. For zero slip:

$$\gamma_2 = \frac{\sqrt{(L/2)^2 - z^2}}{z} \sin^{-1} \left[\frac{z}{\sqrt{(L/2)^2 + z^2}} \right] \tag{222}$$

In accordance with references by Bekker (1956, 1960) and adding metal-soil friction, Ageikin assumed that the soil thrust of the vehicle was:

$$H = NF (1 - \gamma_4) \tau_{aver} + W'_n \gamma_4 \mu_r \tag{223}$$

where NF is the total ground contact area (see equation 208 divided by ground pressure p).

Vehicle load W'_n is only that part of the weight which rests on the wheels, i.e.:

$$W'_n = W_n - \delta_F kNF (z - h_g)^n \tag{224}$$

Value γ_4 in equation (223) is the ratio of the area of the tread which remains in touch with the ground, to the total ground contact area of the tire. μ_r is the coefficient of friction between soil and rubber; τ_{aver} is expressed by equation (217) modified as shown below.

Ageikin considered the triangular load distribution p and its variation with soil type (Bekker, 1956; Söhne, 1956). As a result of his own experimentation he proposed, however, an average shear stress τ_{aver} in accordance with equation:

$$\tau_{aver} = \gamma_5 (c + p \tan \varphi) \tag{225}$$

where γ_5 is a ratio of τ_{max}/τ_{aver} at slip $i_o = 5$ to 10%, which corresponds to shear length $j = 25$ to 50mm, for ground contact length of 40 to 60 cm. Combining equations (223), (224), and (225) gives:

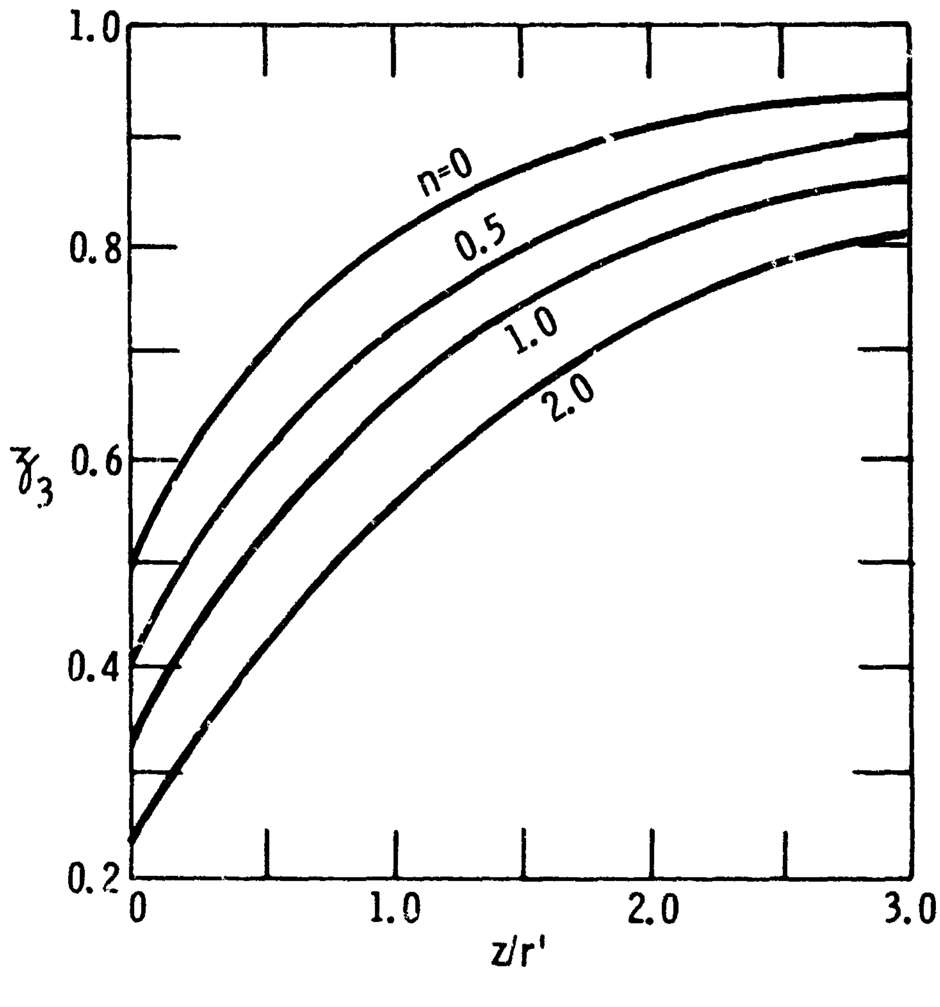


Figure 41 Ageikin's (1960) Coefficient of Tire Side Wall Curvature

$$H = \mathfrak{z}_5 (1 - \mathfrak{z}_4)(cNF + W'_n \tan \varphi) + W'_n \mathfrak{z}_4 \mu_r \tag{226}$$

Direct comparison of equations (219) and (226) provides the answer as to whether the vehicle will go or not, or how it will go, in accordance with the formula:

$$DP = H - R \tag{227}$$

This method provides a parametric tool for selection of the ground contact areas and inflation pressure.

Note that the parameters involved enable the designer to define, for the postulated DP, the following values.

- Tire width B'
- tire diameter D
- tire deflection Δ,

considering such vehicle values as

- ground clearance h_g
- vehicle weight W
- undercarriage structure A' and δ_F,

and soil values

- internal soil friction φ
- cohesion c
- "external" soil friction μ_r
- Bernstein-Letoshnev modulus of deformation k
- exponent of deformation n.

The work by Ageikin represents thus far the most comprehensive parametric analysis of a pneumatic tired vehicle; it was based on the existing knowledge which was subject to attempted refinement by the introduction of a number of empirical corrective coefficients, based on actual vehicle tests. In this manner a pragmatic engineering approach was further enhanced by the Russian automotive engineers.

The Minsk School apparently did not fo[illegible] a similar course of action. In Vol. VII of "Voprosy. . . " Matsepuro and Yan[illegible]ch (1961) reproduced only sketch generalities on tire pressure distribution from Bekker (1956) and Söhne (1958), both quoted in the bibliography.

In the meantime, the Research & Development Automotive Institute (NAMI) and the Moscow Institute of Technology named after Bauman (MVTU im Baumana) conducted extensive experimental work on "super" tires similar to American rolligons. In this program Vlasov and Kuperman (1961) reported among the others, the drawbar pull of tracks ZIL and GAZ equipped with such tires on snow and soil. The main objective of the tests, however, was the life of tires which apparently just went into production. Interestingly, however, the comparison of vehicle speeds equipped with standard and rolligon tires developed in snow 30-35 cm deep also was reported:

Table 25

Vehicle	Speed, km/h	
	Standard Tire	Rolligon Tire
ZIL 164	0.85	9.87
GAZ 51	0.51	2.7
ZIL 151	3.80	-

In a similar work performed under engineers of NAMI, Semenov and Armaderov (1961) tested rolligon tires of 1140x700 size (Ya 146A), using ZIL-150 truck with front wheels equipped with standard 260-20" tires (Russian nomenclature). The objectives of these tests were to:

- Determine motion resistance of the complete vehicle in various terrain types, as a function of inflation pressure
- Compare vehicle performance with standard and rolligon tires in various terrain conditions, including snow
- Determine moments on the driving and driven axles.

One of the interesting highlights of the extensive tests was the optimization of inflation pressure for the minimum driving torque as a function of the depth of snow cover. The result was shown in Figure 42.

It may be deduced from this figure that the minimum driving torque occurs at approximately 1 atm., for all the snow covers. However, the effect of inflation pressure lessens with the increase of snow depth. This was explained by the appearance and increase of snow ploughing by the front bumper, and the other protruding parts of the vehicle.

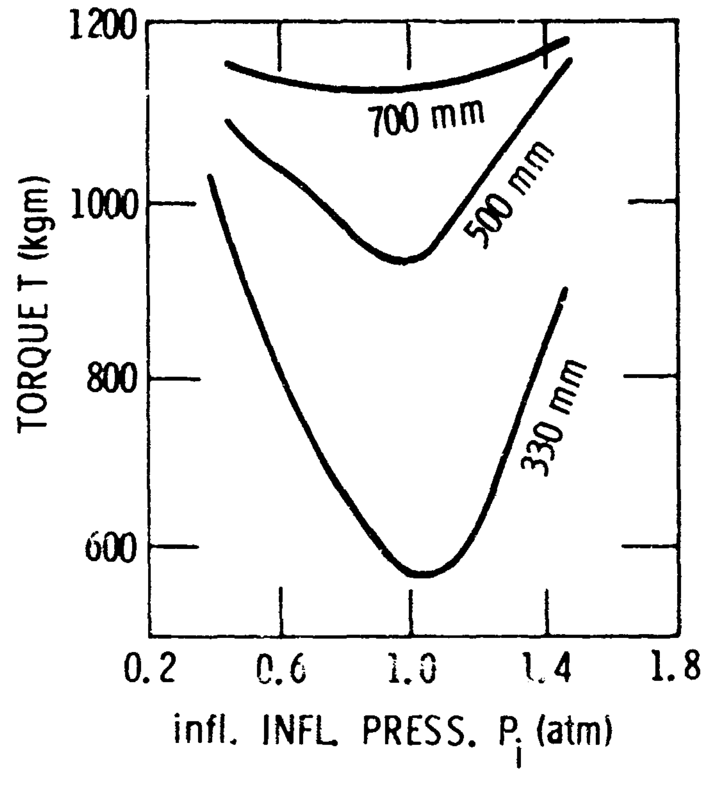


Figure 42 Driving Torque of ZIL-150 on snow of 700, 500 and 330 mm depth at various inflation pressures in rolligon tires. (Semenov and Armaderov, 1961.)

The tests illustrate how misleading may be an analysis of single tires, performed in soil bins; they stress the need for a study of the whole system, which undoubtedly affected first the development of a theory of the tire, and next, of the whole vehicle, as shown by Ageikin (1964).

Numerous tests by Semenov and Armaderov led to the determination of empirical equations for driving torque of the tested vehicle as a function of inflation pressure and terrain type. Thus for pressures $p_i = 0.2$ to 1.0 atm., and for dry sand:

$$T = 1407\, p_i^2 - 1690\, p_i + 933 \tag{228}$$

For grass-covered field to depth of 20 to 30mm with loam subsoil of bearing capacity approximately 20 kg/cm^2, and moisture 10 to 14%:

$$T = 469\, p_i^2 - 900\, p_i + 721 \tag{229}$$

for ploughed, tilled field of chernozem type:

$$T = 656\, p_i^2 - 1100\, p_i + 845 \tag{230}$$

The equations quoted above, although based on interpolation and seemingly insufficient soil value definition, again illustrate the pragmatic engineering methodology which characterized the introduction of the new tires.

Similar work also was performed by the Bauman Institute of Technology in Moscow (MVTU). A strong team of doctorial candidates published another paper on phenomena of moving rolligon type tires on hard and soft ground with particular interest in snow (Bocharov et al., 1961).

In this case, 24" x 36" x 6" rolligons were tested in cooperation with the Scientific Research Institute for Tire Industry (NII Sh P), on a special 4x4 experimental vehicle. A sample of interesting results was shown in Figure 43, which shows that rolling resistance of the rear tires is smaller than front tires. Although theoretically explainable, this experimental finding again stresses the importance of a vehicle study in addition, if not instead of, the study of the single wheel.

In spite of this truism, most of the domestic vehicle laboratories have been concerned more with single wheels than with vehicles. As a result, no theory of a complete

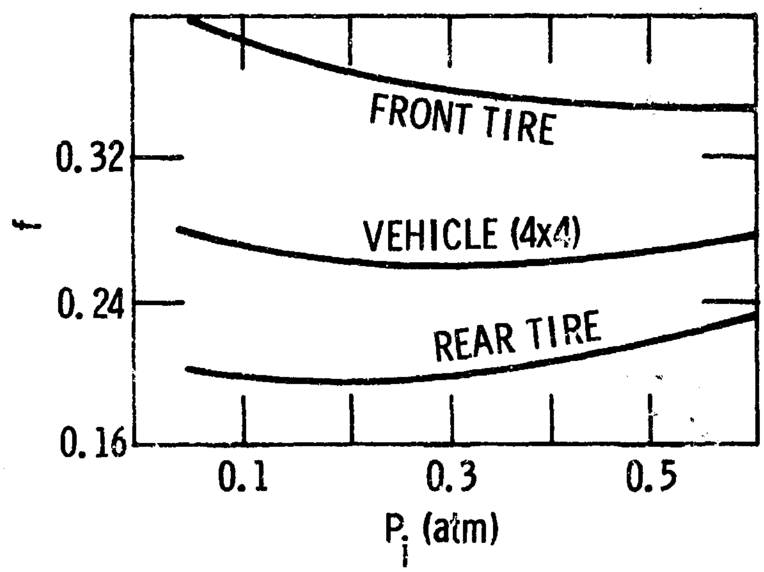


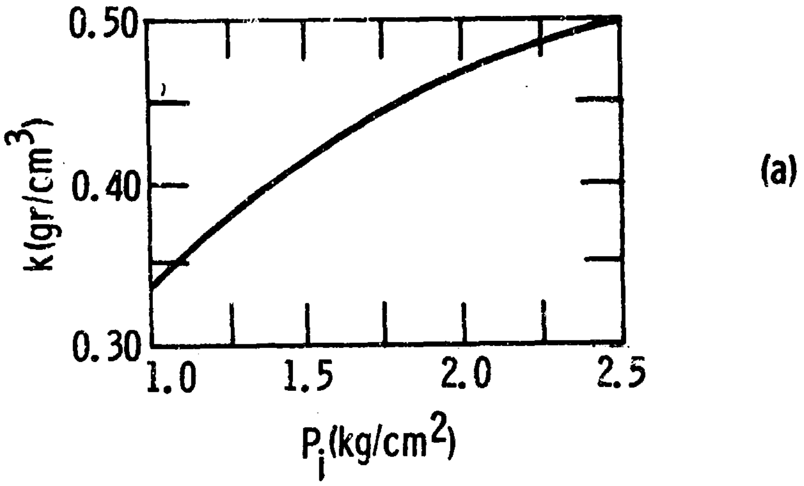
Figure 43 Relation between the coefficients of motion resistance and inflation pressure p_i of rolligon tires (Bocharov et al., 1961).

soil-vehicle system has ever been outlined beyond the preliminary attempt by Bekker (1969 a) and by the Russian investigators whose work will be discussed later, in a chronological sequence.

The rolligon type tires were in the early sixties quite a radical and sensational departure from standard tires, and everyone concerned was testing them. Hence Siliukov (1962) of the Ural Institute for Forest Technology (ULTI) also investigated the application of new tires to the logging vehicle MAZ-501, in snow conditions; the vehicle was equipped with 1300 x 750 tires, model Ya-169. Tests were performed in loose 50 cm deep snow with modulus of deformation $k = 0.2\ gr/cm^3$ on the surface, and $k = 0.03\ gr/cm^3$ at 20 cm depth. The snow was dry, since the temperature was -11^oC. Among other items, the author was interested in snow compaction and in the variation of motion resistance of the vehicle with compaction. Figure 44 shows a typical result. Very neat conservative engineering essay backed by wealth of other measurements and observations.

Armaderov and Semenov (1962) of NAMI followed their previous work (see Semenov and Armaderov, 1961) with further studies of rolligon type tires. Their extensive article is a further elaboration of mobility of trucks equipped with rolligon and standard tires. A sample wealth of information collected was shown in Figure 45, which displays the relationship between motion resistance of truck GAZ-51 equipped with tires, model I-213 (1000 x 600), as a function of slip on a sandy ground. The lesson was that a too low inflation pressure does not pay off – a fact that was previously explained theoretically (Bekker, 1960).

This short review of work by the Russian engineers in the early sixties indicates their extensive preoccupation with pneumatic tires of all sizes. The Russian translation by Fenkin (1962) of Bekker's acticles (1959-1960) published in Machine Design may have influenced their further research, as implied by the doctorial candidates of Bauman Institute of Technology who again published under the auspices of NIIShP more experimental data on pneumatic tires and presented perhaps a first document that included Bernstein-Letoshnev soil measurements for tires obtained by means of the Reviakin instrument.



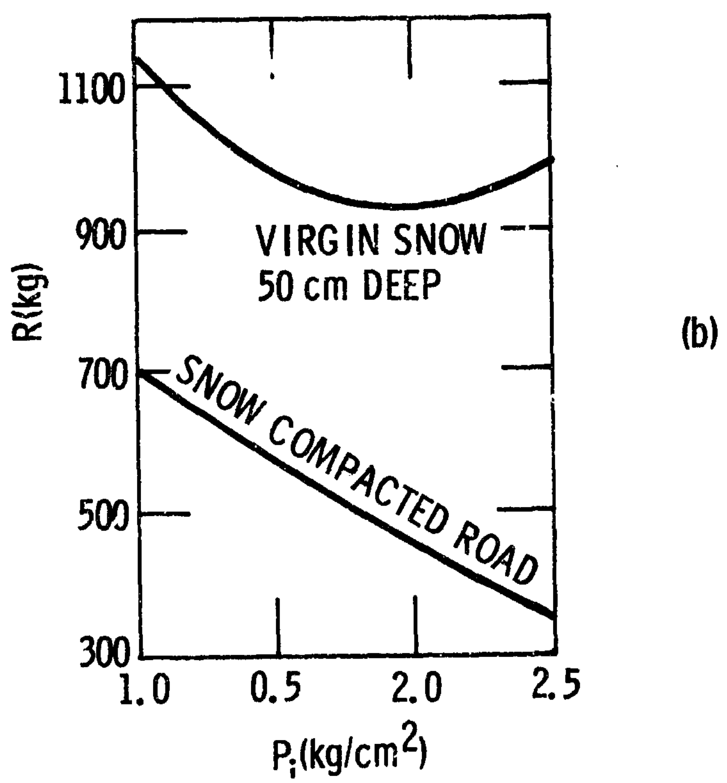


Figure 44 (a) Change in the Modulus of Snow Deformation k as a Function of Compacting Inflation Pressure p_i.

(b) Change in Motion Resistance R as a Function of Inflation Pressure. Vehicle: MAZ-501; Rolligon Tires Ya-169 (1300 x 750). After Silinkov (1962).

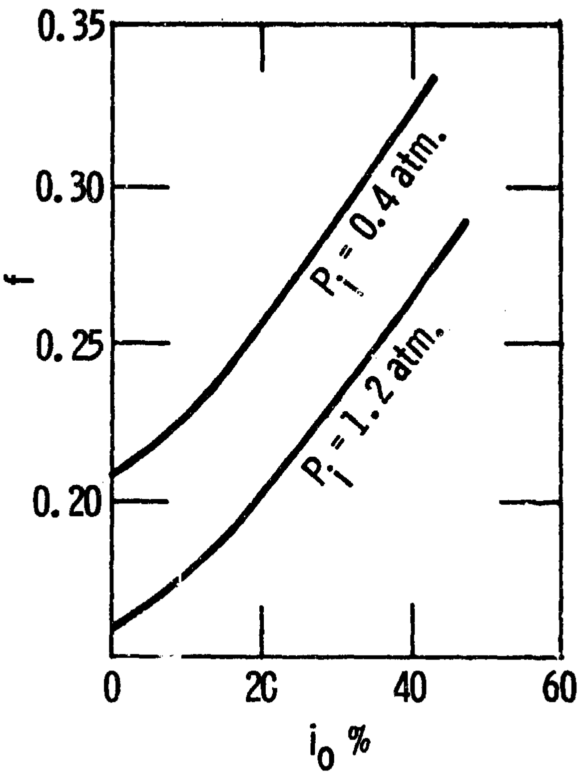


Figure 45 Unit Motion Resistance f of GAZ-51 Truck Equipped With Rolligon Type Tires I-213 (1000 x 600) as a Function of Tire Slip i_o. Sandy Soil (Armaderov and Semenov, 1962).

This document by Bocharov et al. (1963) now became more specific than the previous article by the same authors on the same subject (Bocharov et al., 1961). Although Bocharov et al. basically expanded their old data bank, they become more emphatic in respect to the need for a better soil definition; now a theoretical approach to the problem became not only feasible but also more desirable.

Some impetus in that direction appears also to have come from agricultural engineers, when Shavlov (1963) of VIMe (All Russian Institute for Mechanization) published an article about soil bin testing of a pneumatic tire, in loose ground. In the introduction he thus characterized the state of the art;

> "... all these studies lack methods which would enable one to determine directly, in the field, the optimum ground pressure. There also is a lack of the consideration of the effect of speed, moisture and strength of soil, as well as of surface microprofile, upon the motion resistance, rut depth and tire deformation."

This criticism, however, only led to single-wheel laboratory tests that were almost identical to those performed earlier in the United States (Bekker, 1960). As a result, Shavlov proposed a "new" equation for the critical inflation pressure. This pressure was defined as a limit above which the bottom of the rut is convex instead of remaining flat, i.e., when the wheel behaves as a rigid one:

$$p_{crit} = \sqrt[3]{\frac{9W^2k}{4b^2D}} - p_c \tag{231}$$

How this equation was deduced, was not shown. It is obvious, however, that it is a derivative of Bekker's (1960) equation for critical pressure based on the same definition, if it is assumed that $n = 1$.

What was new in Shavlov's work, however, was an experimental determination of optimum pressure p_{opt} based on p_{crit}, in the following form:

$$p_{opt} = p_{crit}\ (0.3 \text{ to } 0.4) \tag{232}$$

Obviously equation (232) must have been obtained from tests with sandy soil ($n \simeq 1$). Study of speed, moisture, and surface roughness effects were reported in experimental data. Ageikin's (1959) and Zheligovskii's (1960) books on pneumatic tires were

referred to in a three-point list. In spite of the brevity, Shavlov's paper appears to have spurred a more theoretical approach, because of his critique of the state of the art.

Thus, Ageikin's theory was tried when Russian automobile engineers conducted (between 1963 and 1964) extensive soft ground testing of 14.00-20 tires with 4, 6, 8, and 10 plys. These were performed on a 6 x 2 truck under the auspices of MVTU Institute named after Bauman. The measurements included (Filiushkin, 1964):

- coefficient of motion resistance f
- coefficient of adhesion μ_a
- coefficient of towed rolling resistance f

all at optimum inflation pressure. As a result, coefficients of efficiency of various tires in soft grounds were determined. Total motion resistance was considered from the viewpoint of energy spent on ground deformation, tire deflection, and motion resistance on the asphalt. Ground consistency was defined in terms of plate penetration test.

Since, at low sinkage, tire stiffness may play a more important role than soil compaction, Petrov (1966), also from MVTU, investigated internal tire losses and a method of their determination.

The introduction of wide profile tires expanded the test programs. Their objective was on the economy. The tests were performed by the Automotive Research Institute (NAMI) under Armaderov et al. (1964). Vehicles Mark ZIL and GAZ were used. Fuel consumption and statistics of stress distribution under road shocks were recorded. Various types of terrain were included in the measurement of drawbar pull. But the reliability of the vehicles was the main target, rather than tire performance.

However, Strokov (1964), a graduate of Timiriazyev Sielskhoz. Academy, did interesting work on tire theory. In particular, he studied energy E_1 spent on tire deflection and E_2, on soil deformation, using a somewhat academic language in order to express rather simple facts.

The most interesting, and perhaps still underestimated part, of his work was based on the ingenious hypothesis by Academician V. A. Zheligovski. The latter assumed

that the minimum expenditure of work to roll a driven wheel with pneumatic tires, in soft ground, occurs whenever the work spent for soil deformation is equal to the work for tire deformation. The hypothesis was reportedly confirmed by Asanov (1962) and Strokov. It enables one to select optimum inflation pressure for the given soil, thus supplementing work by Shavlov (1963).

According to the simplified reasoning by Strokov, take the functions $E_1 = f_1(p)$ and $E_2 = f_2(p)$ which presuppose no carcass stiffness. The function:

$$E_1 + E_2 = f_1\,(p) + f_2\,(p)$$

has a minimum (with monotonic increase or decrease of both members), when $f_1 = f_2$; then

$$f_1(p) = 1/f_2(p) \tag{233}$$

To test the hypothesis, Strokov used Omelianov's equation (206), which as previously explained is composed of two parts: the first expressing the energy loss in soil deformation, and the second in tire deflection:

$$E_1 + E_2 = \ell\;[\;C_1W\,(p_i/kD)^{1/3} + C_2\,(W^4/p_iD^2)^{1/3}\;] \tag{234}$$

where ℓ is a unit of length.

Accordingly, assuming that equation (233) is valid, the minimum energy expenditure will take place only then, when:

$$\ell\,C_1W(p_i/kD)^{1/3} = \ell C_2\,(W^4/p_iD^2)\;1/3 \tag{235}$$

hence, the optimum inflation pressure p_{opt} is:

$$p_{opt} = \sqrt{\left(\frac{C_2}{C_1}\right)^3\;\frac{kW}{D}} \tag{236}$$

Strokov reported that Gutgar (1953) arrived at the same expression by differentiating equation (234) and equating the derivative to zero in order to determine the minimum of $E_1 + E_2$. Figure 46 shows the energy balance for a driven tire 11.00 - 38.

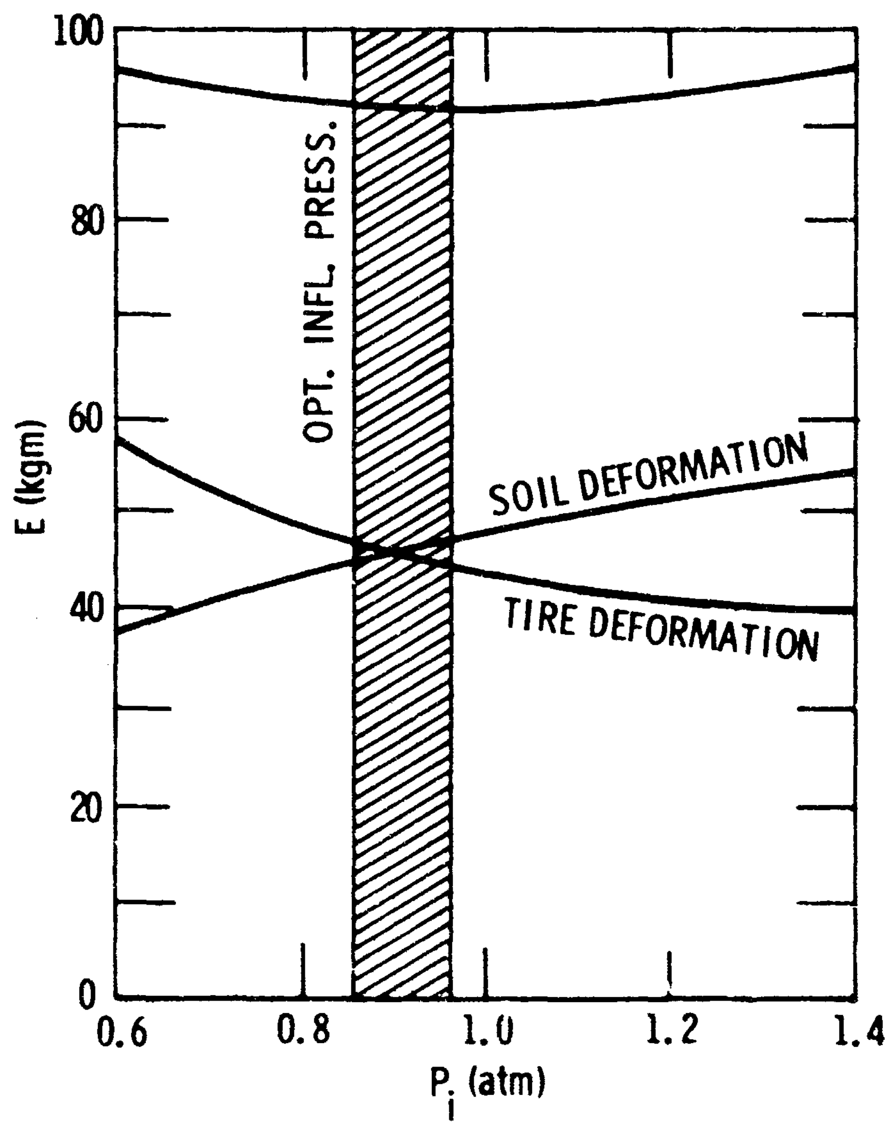


Figure 46 Balance of energy E of a driven wheel 11.00 x 38 as a function of inflation pressure p_i, after Strokov (1964). Soil type and other details were not specified in the available material.

It is unfortunate that Zheligovski's hypothesis was forgotten for more than 10 years until Strokov brought it back to the attention of the engineering world.

In the meantime, prolific students of pneumatic tires from the Moscow Bauman Institute of Technology (MVTU) and Automotive Research Institute (NAMI) produced more experimental data in defiance of any theoretical reasoning. Nevertheless the data bank by Bocharov et al. (1964) has a great value for analyses of tire mechanics per se: information primarily contains data on static and dynamic "rolling" radius vs driving moments, on both soft and hard ground, based on field tests.

At the same time the representatives of the Minsk School were systematically evolving a tire theory based on the assumption that an elastic wheel may be substituted with a rigid wheel of an appropriate size. The substitute size depends on tire size, its rigidity, and on the Bernstein-Letoshnev soil value system. Thus, they (Guskov, Kuzmenko, and Badalov, 1964) deduced for a tire, a motion resistance equation which structurally was similar to that for a rigid wheel.

Their theory was discussed in conjunction with soil-value problems in Chapter II,, and it is suggested the reader see equations (47) to (51).

The theoretical solution for soil thrust acting upon a tire, which also was introduced, appears to be somewhat artificial and is of unknown origin. The authors start with modified Coulombian equation of unit thrust:

$$\tau = (c + p\tan\varphi)\sqrt{j/j_0} \tag{237}$$

which was discussed in connection with the rigid wheel (see equation (164)). The cohesive component of thrust was then expressed by formula:

$$H_c = c\,(\sqrt{jD\Delta} + 0.25\, D\Delta i_0/\sqrt{j}\,) \tag{238}$$

and the frictional component:

$$H_\varphi = c_t\,\Delta\sqrt{D\Delta j}\,(0.66 + 0.125\, i_0\sqrt{D\Delta/j})\tan\varphi \tag{239}$$

where $j = r\,\alpha_1 i_0$; α_1 is the front end ground contact angle as denoted on Figure 25. Total tire thrust H was assumed as: $H = H_c + H_\varphi$.*

* Dimensional structure of equations (238) and (239) is obscure.

This treatment of the problem certainly was the first approach by the Minsk School to elastic wheels; it was brief, unclear, and incomplete. The bulk of information on this subject dealt with empirics not much different from that reported previously, but contains much practical information on tire selection for agricultural tractors.

Since the mechanics of the tire itself was not quite well defined, work in this area progressed steadily (Nadezhdin 1964). However, with the growing need for theoretical solution of tire-soil interaction, additional soil-tire theories were appearing too. Thus, work by Kosharnyi (1966) published in the proceedings of the Ukranian Institute of Mechanization and Electrification of Agriculture is of interest, and has a certain significance, although it differed little from previous theories. Kosharnyi quoted 5 references, of which one referred to Ageikin (1959) and two to Bekker (1956, 1959-60).

His theory of a pneumatic tire was thus based on the assumptions of Coulomb $\tau = c + p \tan \varphi$ and Bernstein-Letoshnev soil-values: $p = kz^n$. The profile of the deflected tire also was practically the same as in the quoted references. (It is known today that this was not quite correct, see Bekker, 1969.) The only tangible refinement introduced by Kosharnyi was the effect of soil friction along the lateral tire walls. In all probability this was of little significance.

The article was written in pretentious language which obscured the simplicity of the issue. It did not refer to Belorussian Institute of Mechanization and Electrification of Agriculture. Apparently it was a long way from Kiev to Minsk.

The basic line of Kosharnyi's thought was not new, as mentioned before, and the motion resistance was assumed to be:

$$R = \int_F kz^n \, dF \tag{240}$$

soil thrust:

$$H = \int_F \tau \, dF \tag{241}$$

drawbar pull:

$$DP = H - R \tag{242}$$

All these values were expressed per unit load, i.e., in terms of $\mu_T = H/W$, $f = R/W$, and $\mu_a = DP/W$.

The main problem was to determine the distribution of stresses τ and $p = kz^n$, along the flattened bottom portion of the tire, the round front portion, and the side walls of two cross-sectional forms: round and/or trapezodial. The same problem existed with the definition of corresponding load surfaces, F's.

It is probably of little interest to follow Kosharnyi's arithmetic and geometry as well as the simplifying assumptions he made in order to solve equations (240) to (242). The practically insolvable complexity of similar equations, documented somewhat later by Schuring (1968), was known to the author. As a matter of record, see the solutions of equation (240), for a tire with rounded side walls, and n = 1:

$$f = (F_0/W)\, 0.5\, kz\, (1 + 1.6\, \mathfrak{z}') \tag{243}$$

where $\mathfrak{z}'$ is a coefficient introducing the augmentation of the area of rut cross-section, due to the expansion of the lateral tire profiel. F_0 is the width b of the tire ground contact area multiplied by sinkage z: $F_0 = bz$. Coefficient $\mathfrak{z}'$ was defined as:

$$\mathfrak{z}' = (4/3)\ (\mathfrak{z}''/b)\sqrt{z} \tag{244}$$

and $\mathfrak{z}''$ was only defined as an "empirical coefficient" which determines the height of rounded up side walls sunken in the ground. Since the definition of load surfaces and projection of stresses in equation (241) was considered too difficult (the author complicated the issue by introducing grouser effect), Kosharnyi depended on experimental measurements or assumed the old solution (Bekker, 1960):

$$\mu_T = H/W = \tan\varphi + (A'/W)\, c \tag{245}$$

where A' is the horizontal grouser contact area of the flattened tire portion. The solution of equation (242) was obtained from equations (240) and (241): $\mu_c = \mu_\tau - f$. The value of z in equations (243) and (244) was given in the following form:

$$z = \frac{W + \mathfrak{z}''' k}{\mathfrak{z}^{iv} k} \tag{246}$$

where $\mathfrak{z}'''$ and $\mathfrak{z}^{iv}$ are empirical coefficients of the given tire, depending on its radial deformation in soil. Apparently equation (246) refers to soil with n = 1, since n does not enter into that equation.

Kosharnyi did not produce data on $\mathfrak{z}'''$ and $\mathfrak{z}^{iv}$; he stated, however, that motion resistance due to the friction of lateral tire walls was insignificant ($f \cong 0.01$). Since this could have been anticipated, his conclusion that the introduction of friction could not be expected to improve the Ageikin-Bekker tire theory was obvious. Nevertheless, his work was significant as it proved the existence of a strong trend towa. l a synthesis of the existing theories and empirics, and the influence of American work.

It should be noted that at the time when the Ukranian agricultural scientists theorized on tire performance, and measured k, n, c, and φ soil properties using Reviakin plate penetrometer, the American agricultural engineers (McLeod et al., 1966) still used the cone penetrometer (never used by the Russians for predicting soil-vehicle parameter interaction), and defined soil properties in such irrelevant "values" as bulk density and pressures measured at arbitrary points by strain-gauge cells. This they did without any reference to the American work, which was used as a springboard by Koskarnyi. But Kosharnyi (1966) did the same to his colleagues in Minsk. Apparently, research needs some coordinating management in both countries, without impairing the freedom of individuals.

In the meantime the Minsk School was not dormant. Guskov in 1966 published a book on optimization of tractor parameters. It was based on his own work, including that by NATI (Scientific Institute for Tractor Research) and by VIM (All Russian Institute for Motorization) which was acknowledged in the preface.

Guskov's book based on well established evolutionary pragmatism was methodologically ahead of anything done by his contemporary agricultural colleagues (compare Gill and Vanden Berg, 1967). His approach to the pneumatic tire was as follows.

First he referred in detail to Omelianov (1948) whose work was discussed earlier in this chapter. Next, he briefly dismissed work by A. K. Birulya, describing it as a "study of non-linear deformations of two contacting bodies." Work by O. T. Batrakov, characterized as a "case of localized loads of a movement-free envelope," also was not described in detail. Finally, an analysis by G. B. Bezborodova was mentioned as a study of "rolling upon the ground of a large number of bolts of a very small size," and dismissed.

Reference to the little known recent work by Lvov (1960) brought the reproduction of his equation of rolling resistance of an elastic wheel:

$$R = 0.86\ \varkappa\ W\ \sqrt{\varkappa W/bk\lambda_o^2\ D^2} \qquad (247)$$

where $\varkappa W$ is the load acting upon the front cylindrical tire portion; $\lambda_o D$ is the diameter of that portion. Coefficients $\varkappa$ and λ_o depend on inflation pressure and mechanical properties of soil. No values were given.

Tests by Babkov (1959) and Gennikh (Hennig?) (1959), referred to by Guskov, allegedly led to the conclusion that the ground contact area of a tire may be replaced by the ground contact area of a larger wheel, which was discussed in connection with equations (51) and (163):

$$D_{\text{rigid wheel}} = \frac{D_{\text{tire}}(c_t+k)}{c_t} \qquad (248)$$

Now, Guskov has reported that A. L. Marshak deduced for $D_{\text{rigid wheel}}$ and D_{tire} the following reciprocity:

$$D_{\text{rigid wheel}} = \frac{kD_{\text{tire}}}{c'_t} \qquad (249)$$

where $c'_t = c_t k/(c_t+k)$. Obviously equations (248) and (249) are identical, considering c'_t value. For inflation pressure $p_i = 0.8$ atm., $c_t = 0.26$ kg/cm^3. This approach was justified, as Guskov put it, with "studies conducted abroad, in particular by M.G. Bekker (1955)." Guskov also quoted McKibben et al. (1939, 1940) who as he said:

> "showed experimentally that a pneumatic tire produces a larger ground contact area than a rigid wheel of the same diameter."

Nevertheless he was aware of oversimplification, and expressed preference of the theory by Babkov (1959). Here, too, a pneumatic tire was considered as a rigid wheel of an appropriate larger diameter (Figure 47).

From Figure 47 the following goemetrical relationships were deduced:

$$\sqrt{D(z - \Delta)} = \sqrt{D_1 z} \qquad (250)$$

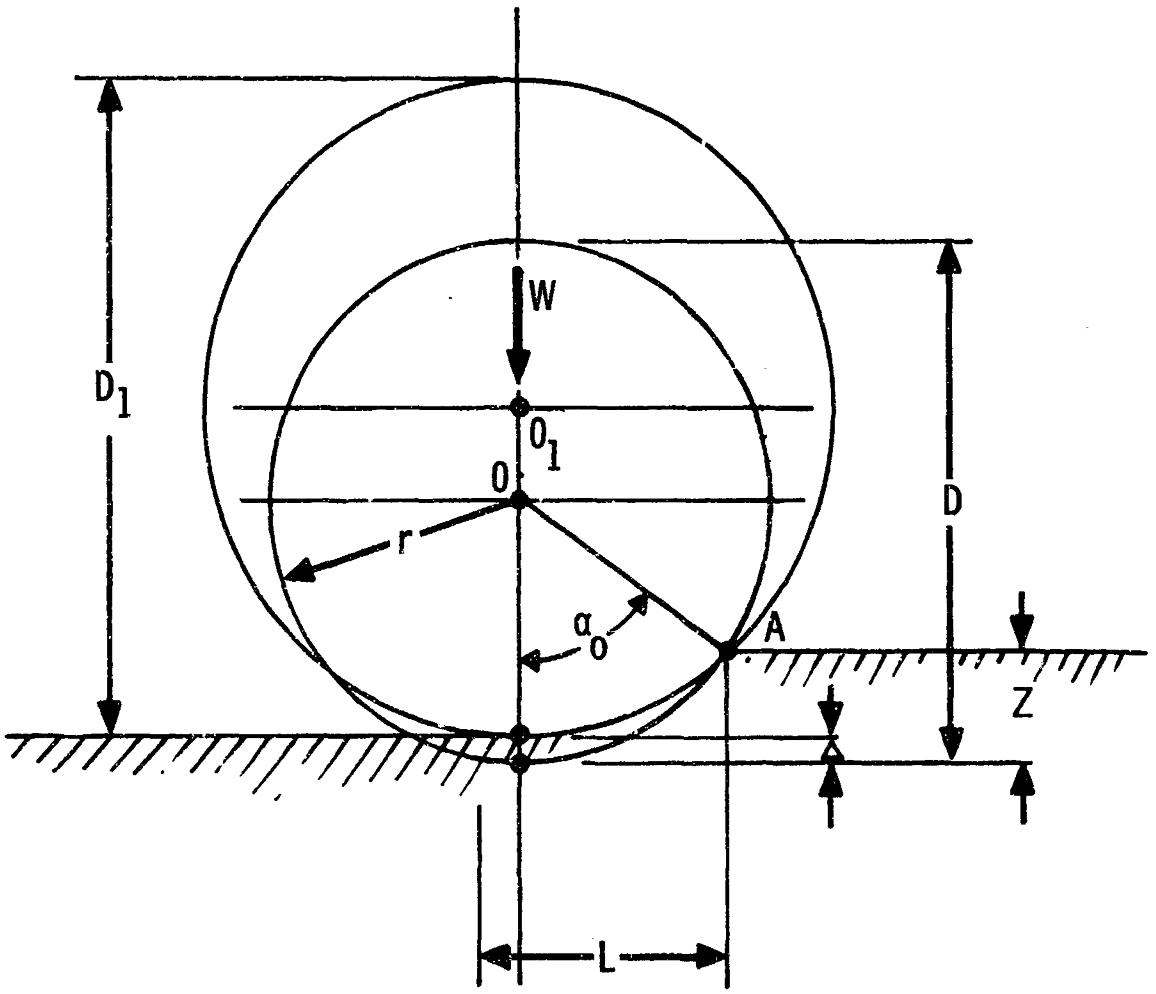


Figure 47 Elastic Versus Rigid Wheel (Babkov, 1959). Quoted From Guskov (1966).

and

$$D_1 = D\,(1 + \Delta/z) \qquad (251)$$

where D is the tire and D_1 the substitute rigid wheel diameter. O and O_1 are their respective centers. Both the tire and rigid wheel rim pass through the point A, and the curvature of wheel D_1 is practically the same as the curvature of the deformed tire.

Guskov, mentioning Khedekel (whom he did not list in the references),* adapted his formula for radial tire deflection Δ:

$$\Delta = W/\pi\, p_i \sqrt{2r_1 D} \qquad (252)$$

where r_1 is the radius of curvature of the tire in ground contact. In addition, adapting for sinkage z formula (see equation 194):

$$z = \sqrt[3]{W^2/k_{KA} b^2 D} \qquad (253)$$

He solved equations (250) - (253), obtaining:

$$D_1 = D\left[1 + \sqrt[3]{Wk^2_{KA} b^2} \Big/ \pi\, p_i \sqrt{2r_1} \quad \sqrt[6]{D}\right] \qquad (254)$$

The resistance to motion of the rigid wheel due to soil compaction was assumed (compare equations (107 - 109)) as follows:

$$R = 0.5\,\sqrt[3]{W^4/k_{KA}\, bD_1^2} \qquad (255)$$

For a 12 - 38" tire with $p_i = 0.8$ kg/cm^2, and D = 157 cm the substitute rigid wheel diameters D_1 are shown in Table 26.

Table 26

W(kg)	0	500	1000	1500	2000	2500	3000	3500
D_1(cm)	157	250	275	290	306	317	326	336

* This name refers to the British Engineer R. Hadekel (1952) who produced an extensive reference book on aircraft tires.

Soil value k_{KA} used in the computation of Table 26 was measured with the Revyakin plate penetrometer showing $k''_{KA} = 10\ kg/cm^2$. Hence k_{KA}, according to equation (26), was assumed as:

$$k_{KA} = \frac{k''_{KA}}{\sqrt{Db}} = \frac{10}{\sqrt{157x32}} = 0.14\ kg/cm^3$$

Figure 48 shows computed values of R and z for the same soil tire and inflation pressure as above, and for various loads, W, in comparison with a rigid wheel of the same overall dimensions as the tire.

Soil thrust of a pneumatic tire also was subject to special consideration. Equations deduced in Guskov's book were based on Katsygin soil values. Length L of the ground contact area was assumed as follows (Figure 47):

$$L = r\alpha_o + \sqrt{2r\Delta} \tag{256}$$

where

$$\alpha_o = 2\tan^{-1}\left[\frac{r - z}{\sqrt{Dz}}\right] \tag{257}$$

For the sake of simplicity, the slightly curved ground contact area of the tire was replaced with a horizontal plane. Triangular load distribution was further assumed and reference (Bekker, 1956) was quoted in that respect. Hence soil thrust H was:

$$H = \int_o^L b\tau\, dx \tag{]58}$$

Difficulty and complexity in defining τ distribution along L was stressed by Guskov. However, he assumed that Katsygin's equation (29) gives a sufficient approximation of relationship between ground pressure p and other variables as discussed previously (see equations 30 and 31). Accordingly, H was expressed by equation:

$$H = \int_o^L b\mu_m p\left[1 + \frac{\mu_{KA}}{\cosh(i_o x)/k_\tau}\right]\tanh(i_o x/k_\tau)\, dx \tag{259}$$

Guskov also realized that ground pressure p is not evenly distributed along L but changes as an undefined function of x: p = f(x). He felt it safer, however, to assume

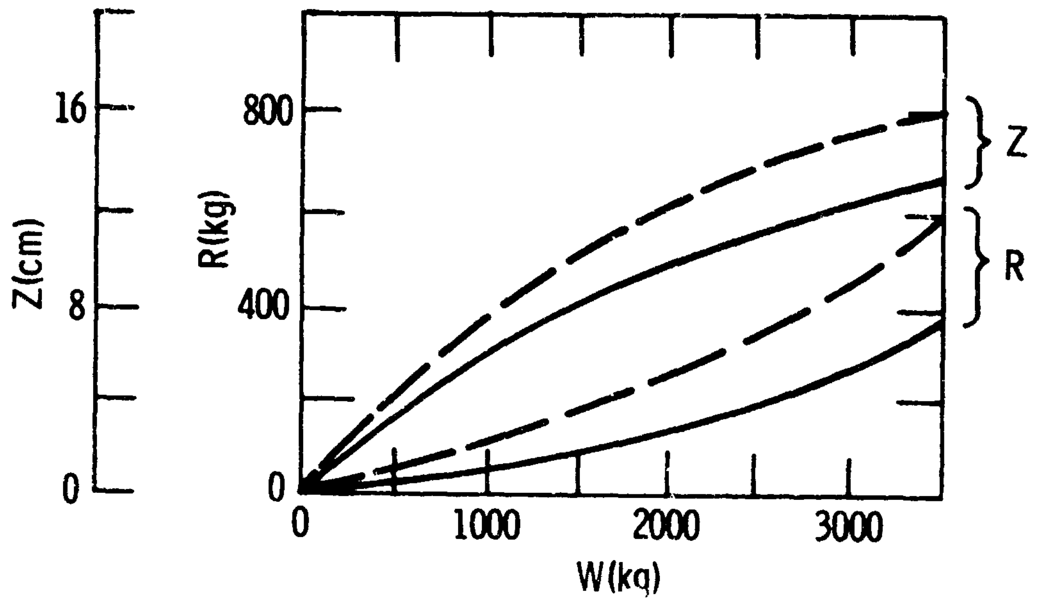


Figure 48 Relation Between Motion Resistance R, Sinkage z, and Load W, on Silty Stubble Soil. Soil Value $k_{KA} = 0.14$ kg/cm^3.

Solid Lines — Pneumatic Tire: 12-38" (D = 157 cm., b = 32 cm., $p_i = 0.8$ kg/cm^2. Interrupted lines -- Rigid Wheel: D=157 cm., b = 32 cm. After Guskov (1966).

that p was uniform, rather than to introduce τ in equation (258) as a constant. Accordingly, for p = constant integration of equation (259) yielded an:

$$H = \left[bp\mu_m k_\tau / i_o \right] \left\{ \ln \cosh (i_o L/k_\tau) - \mu_{KA} \left[1/\cosh (i_o L/k_\tau) - 1 \right] \right\} \tag{260}$$

All the coefficients were defined in equations (28) to (31), and exemplified in Table 9.

Equation (260) was refined by introducing tire tread effect, which seems to be rather superfluous in view of other simplifying assumptions. The additional tread thrust H' was expressed by equation:

$$H' = 2\,\tau_t\,(hL/\ell) \tag{261}$$

where h is the height of the protruding tread and ℓ is the spacing between the tread bars. τ_t measured in kg per cm of length was determined in numerous tests and found to be changing very little:

Stubble, on medium hard silty soil:	τ_t = 1.26 to 1.94 kg/cm
Stubble, on loose sandy soil:	τ_t = 1.5 to 2.6 kg/cm

Guskov's presentation of performance of the pneumatic tire was again typical of the simple engineering approach: instead of embarking upon rigorous solutions which cannot be attained because of undefinable boundary conditions and other necessary assumptions, he proceeded with relatively simple integrals, in which the uncertainties were taken care of by means of empirical coefficients.

As has been shown previously, this was a typical Russian approach. They never embarked, as far as could be ascertained, upon super scientific, rigorous solutions, or upon antiquated empirics which have been tried without practical success in the United States and Canada.

More theoretical approach has been reported only sporadically (compare Glagolev and Poletayev, 1967) and, in all probability has never been as extensive and time and money consuming as in this country. Apparently only we could afford the luxury of theorizing on what either has been known empirically for years, or what could be found in a simple test.

The approach similar to the Russian approach is clearly seen in Hungary (Sitkei, 1967; Komandi, 1968), Poland (Soltynski, 1966; Wislicki, 1969), Czechoslovakia (Grecenko, 1967), and Romania (Mihatoiu, 1970).

The spirit of practical engineering rather than scientific sophistry was so strong that the Russian civil engineers who were interested in earthworks and earthmoving machinery simplified the problem of tire evaluation by assuming quasi-elastic ground properties.

This was totally justified since terrain must be improved, if necessary, before any major earthworks can be completed. Under these circumstances, tires of scrapers and dirt transporters may be evaluated with the assumption of $p = kz$, where k becomes a value close to the Young modulus.

A very fine and strictly practical, yet still high caliber, presentation of such a simple method was made by Ulianov (1969) in the book on the theory of transporters and machinery used in earthworks. No "California Bearing Ratio" and no "Cone index" or "G-value" were ever used; simple principles of regular applied mechanics sufficed to produce the work which, to the best knowledge of this writer, has no parallel.

Apparently Russian engineers were aware of the futility of trying to obtain a rigorous or oversimplified solution for such a complex subsystem as the wheel and the soil – futility which was demonstrated with great clarity by Schuring (1968).

Figure 49 shows the experimental rolling resistance coefficient f versus relative sinkage z/r adapted from Schuring's work, wherein he analyzed 25 wheels in 10 different soils. Some of the data were averaged in a single line, the other in a band of width covering the wider scatter. The smaller sinkage data ($z/r < 0.03$) were not considered in the adapted graph because such information is subject to soil properties variation, and to strong tire stiffness effect which apparently was not evaluated. The result shows how close test data are to the basic Bernstein-Letoshnev-Bekker line: $f = k\sqrt{z/r}$. Considering differences in techniques of tests by various investigagors, and different tires and soils as well as lack of soil specification, one cannot help but remain amazed that tires behave so uniformly and are so close to the basic line, at practically significant sinkage.

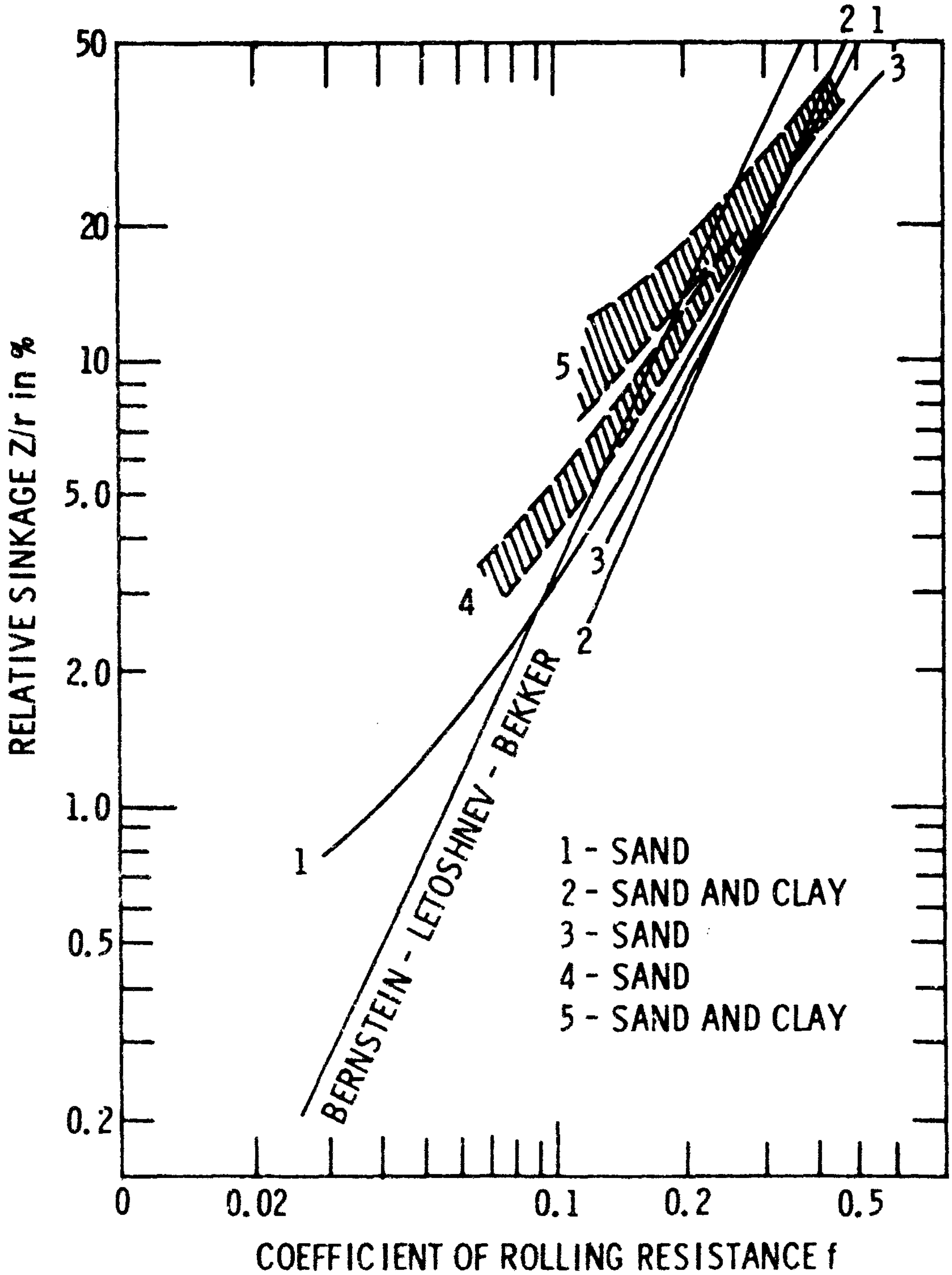


Figure 49 Averaged Test Data (About 1000 Tests With Approximately 20 Tires in 10 Different Soils) For Various Pneumatic Tires; and Soils, by Various Investigators. Adapted From Schuring (1968).

The chapter on pneumatic tires may thus be closed with the statement to the effect that Russian work performed for the past 30 years, in general, did not waste time on generalized grandoise schemes or naive empirics, but concentrated on pragmatic solutions of particular cases. Yet the solutions were broad enough to yield themselves to simple parametric evaluations of terrain-vehicle systems, as will be shown in the next chapter.

Of course, there is room for improving predictive capacity of tire theories, particularly of low sinkage. But the room is rather small, and as past experience indicates, even slight improvements are very expensive. Thus the tradeoff between the gain and the cost of any new theory must have been weighed carefully by the Russians, since they did not indulge in the extravaganza, which frustrated their American colleagues in the past decade.

Tracks

Serious theoretical approach to a track, and attempts of mathematical modeling of track-soil interaction did not start, as far as it could be ascertained, before 1950. A small classic by Zaslavski (1932) was a predecessor of track's applied mechanics, but it was not concerned with soil properties "per se." In the same category are works by Medvedev (1934) and Kristi (1937), conducted for the military for tank design. However, work reported by Kristi also was adapted to the design of tracks of agricultural tractors (Kristi, 1938), although track-soil relationship again was neglected, undoubtedly because of the emergence of overwhelming problems of design (compare Bekker, 1956).

A few years later, Gruzdev (1944) devoted more attention to the soil problem. He dwelt at length on the rigid wheel theory, assuming parabolic ground pressure distribution which led him to the definition of motion resistance in terms of sinkage and wheel size (see Table 21). But when it came to the track, he resorted to dynamometric empirics, and did not produce any significant theory of track-soil interaction. However, the kinematics, and mechanical efficiency of tracks "per se" were worked out in such a fine mathematical detail that even today it would be difficult to find a more exhaustive work on this subject. Much of this work was borrowed from Kristi's (1938) book: solutions were based on equations of equilibrium, and were not much concerned with track dynamics and equations of motion. This, however, does not diminish the importance of this classic.

Martens (published after 1948), who edited a book on Automotive Theory, also did not develope the track-soil theory, although he fully adopted Bernstein-Letoshnev's formulae and soil values for wheel evaluation. He used empirical coefficients of adhesion and motion resistance for an evaluation of design parameters.

All this indicates that the track-soil problem was far behind the wheel, from the theoretical viewpoint. Moreover, there seems to be a gap in the Russian literature on track-soil relationship, covering the period from 1950 to 1960.

In 1950, Bekker's theory on land locomotion was published in the Proceedings of the Society of Automotive Engineers, and in 1956 in book form by the University of Michigan Press; both were almost immediately translated into Russian.

In Volume III of the Minsk "Voprosy... " (1960), Bekker's work was referred to in detail, which indicated the entry of his school of thought into the Russian intellectual system However, the system worked very slow and/or in a hesitant manner, since the referencing was based on the 1950 publication by the Society of Automotive Engineers, although the 1956 book published by the University of Michigan Press was unmistakably reviewed. In any case the American work echoed in the U. S. S. R.

In 1960, Zapolski published in Volume V of the "Voprosy... " the description of the instrument originally devised by Bekker for testing the shearing forces between the track and the soil (see Figures 21 and 22). In the same volume Katsygin and Aziamova (1960) dwelled at length on measurements of Bernstein-Letoshnev soil properties k and n, as defined by the basic equation $p = kz^n$, which at the same time was expanded by Bekker (1960) into the present form, $p = [(k_c/b) + k_\varphi] z^n$.

The process of assimilation of new ideas is very slow at the beginning; it is cautions and rejective rather than adoptive. Since social and psychological traits of human nature are basically the same in the whole world, Russian engineers could not be expected to react to the American achievements in a different manner.

Hence, Sofian and Maksimenko (1960) began testing their own schemes of distribution of shearing (tangential) forces beneath the track, using a DT-54 and S-80 tractor data, for soils with k = 0. 7 - 0. 8 and 5-6 kg/cm^3, and n apparently equal to a unit. They referred to Bekker's (1955) work, reproducing a few of his theoretical diagrams, and

noted the basic similarity between the results of the theory and their experiment. In conclusion, they voiced, however, the need for further development of the theory which deals with real flexible, nonuniformly loaded track chain, instead of with an ideal rigid uniformally loaded track.

As will be shown later, the Russians tried to do it. But we never did. This is one of the tangible examples that indicate our slipping behind the progress fostered by the others, though originated by ourselves.

The process of further assimilation of American work by the Institute of Mechanization and Electrification (IMESH) of the Belorussian Academy of Agricultural Sciences (ASHN) is clearly seen in Chapter I of "Voprosy..." (Volume VI), written by Matsepuro and Guskov (1961). Both authors dwelt at length on references (Bekker, 1956 and 1957). As a result they attempted to further expand the theory and, if possible, to imprint the seal of their originality on the ideas which came from America.

First, they determined the ground pressure under the catenaries of tracks stretched between two bogie wheels. To this end, simplified drawings were borrowed from reference (Bekker, 1956) and the calculation also was performed for $n = 1$ (i.e., $p = kz$).

The main difference between the Russian and American solutions was in the denotations, and in the Russian preoccupation with ground pressure p_x, while we worked with sinkage z_x of the track of point X. Accordingly, sinkage of the track at that point located at distance x from the centerline of the catenary was determined from a familiar equation:

$$p_x = W_b k e^{x\sqrt{kb/H_o}} \Big/ 2\sqrt{kbH_o}\left[e^{.5\ell\sqrt{kb/H_o}} - 1\right] \tag{262}$$

where H_o was track tension and ℓ was the distance between the wheels.

Equation (262) led to the introduction of the new coefficient of nonuniformity of track pressure β_t:

$$\beta_t = (p_{max} - p_{min}) / p_{aver} \tag{253}$$

Since p_{min} takes place at x = 0, and p_{max} at $x = \ell/^{\gamma}$ (see Bekker, 1956), Matsepuro and Guskov deduced from equations (262) and (263) that

$$\gamma_t = 0.5\ \ell \sqrt{kb/H_o} \tag{264}$$

This led to the discussion as to how to design parameters b, ℓ, and H_o for soil parameter k in order to produce greater or smaller nonuniformity of track pressure distribution (compare similar discussion in Bekker, 1956 and 1960). Obviously such a discussion would be totally impossible with soils measured in "cone index."

The analysis by Matsepuro and Guskov of the soil thrust was based on the summation of elementary shear deformations j of soil under the track grousers, which were assumed as increasing in the linear fashion (Bekker, 1956). Thus, the work of shear by N grousers, for two tracks was:

$$E' = \sum_{N=1}^{N=N} 2\ (khbjj + khbj2j\ldots + khbjNJ) = khb\ (1 + N)\ NJ^2 \tag{265}$$

and the work of shear by lateral sides of the grousers:

$$E'' = 2\ \tau_{av}\ (2h + b)\ Nj \tag{266}$$

where τ_{av} measured in kg/cm is a shear stress per cm of length of grouser partmeter.

It is difficult to explain how the k-value which, according to Bernstein-Letoshnev denotes sinkage modulus in vertical direction, was used by Matsepuro and Guskov to denote the modulus of horizontal shear.

However, it should be noted that this was tolerated by a number of Russian investigators of the rigid wheel who also assumed k-values as representative of non-vertical soil deformation along the cycloids of soil movement. Nevertheless, such an assumption can only lead to trouble and, as will be shown later, the Russian investigators used Coulomb's equation (Bekker, 1948, 1950, 1956), though it was modified in mathematical manipulation.

The work of grouser shear E' and E'', equations (265) and (266) was augmented by Matsepuro and Guskov by the work E''' defined as the work of track friction under load W, at distance $\ell_t - j$, where ℓ_t was the track pitch:

$$E''' = W\mu_o (\ell_t - j) \tag{267}$$

Thus the soil thrust H developed by the track was obtained by adding works E', E'', and E''', and by dividing the result by distance $\ell_t - j$, where j was assumed as an average:

$$j = \ell i_o / N \tag{268}$$

Here, ℓ denotes the length of the track on the ground. Accordingly:

$$H = H\mu_o + \frac{Ni_o}{1 - i_o} \left[khb \frac{(1 + N)\ell i_o}{N} + 2\tau_{av} (2H + b) \right] \tag{269}$$

Equation (269) looks attractive since it expresses H in terms of track dimensions, soil properties, and slip. However, this writer could not find an experimental verification of the formula, although much testing of H was reported by the Russian authors.

The only conclusion they reached was that field tests confirmed the validity of the form of equation (269), inasmuch as it was composed of load factor $W\alpha$ and ground contact area factor $A'\beta$ (where α and β are load and area factors, respectively):

$$H = W\alpha + A'\beta \tag{270}$$

This obviously was nothing else but the basic Coulombian equation introduced by Bekker (1948, 1950, 1956) in the form:

$$H = W \tan \varphi + Ac \tag{271}$$

Significantly enough, Matsepuro and Guskov knew it. Anyway, equation (269) did not seem to have survived long, and was superceeded by another one, as will be shown later.

Motion resistance R of two tracks was determined on the basis of Bernstein-Letoshnev soil values $p = kz^n$, for n = 1. To this end, the authors quoted equation: $R = bkz^{n+1}/(n+1)$ (Bekker, 1950, 1956), which produced two-track resistance as:

$$R_{Bek} = bkz^2 \tag{272}$$

However, they were critical of the accuracy of formula (272), without specifying the reason, though these were well known since the early thirties. They were also unhappy with a solution subscribed to A. C. Antonov who proposed to treat the track on the same basis as a rigid wheel:

$$R_{Ant} = 0.54 \sqrt[3]{W^4/kbr^2} \tag{273}$$

where r was the sprocket radius.

To obtain a better formulation for motion resistance R than in R_{Bek} and R_{Ant} equations, the authors described the following original approach. Consider the "angle of approach" portion of the track (Figur 50). Since all the ground reactions acting upon the track are parallel if the track is assumed to be rigid, the resultant reaction R_t is:

$$R_t = \int_A \sigma \, dA \tag{274}$$

where A is the projected track area of the "approach portion," and σ is the respective ground stress. The projection followed the direction perpendicular to the absolute velocity v_o of the track with reference to the ground in the following manner (Figure 50):

$$dA = b \, d\ell \cos(\theta + \alpha/2)$$

or, since

$$d\ell = dz/\sin\alpha \tag{275}$$

$$dA = b \, \frac{\cos(\theta + \alpha/2)}{\sin\alpha} \, dz \tag{276}$$

where θ denotes the angle between the direction of the absolute speed $\bar{v}_o = \bar{v}_T + \bar{v}_A$ at a given slip, and the firection of $\bar{v}_o$ at zero slip.

Values of θ, or rather of $\cos(\alpha/2 + \theta)$ and $\cos(\alpha/2 - \theta)$ which enter the final solution, were expressed in terms of v_A/v_T ratio in the following form, considering that $v_A = (1 - i_o) v_T$:

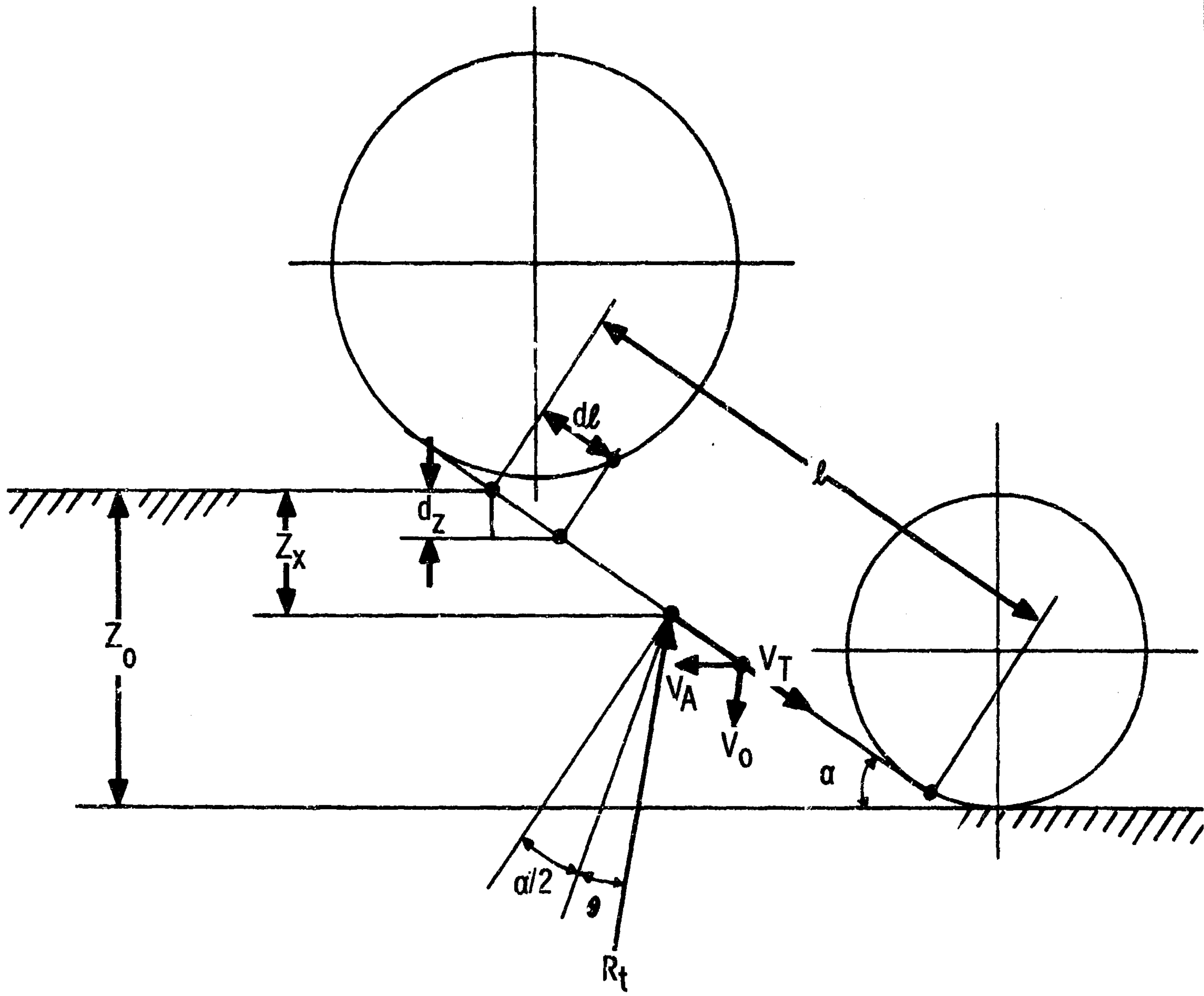


Figure 50 Simplified Matsepuro, Guskov (1961) Scheme For Determination Of Track Motion Resistance.

$$
\left.
\begin{aligned}
\cos\left(\frac{\alpha}{2}+\theta\right) &= \frac{(1-i_o)\sin\alpha}{\sqrt{2(1-i_o)(1-\cos\alpha)+i_o^2}} \\
\cos\left(\frac{\alpha}{2}-\theta\right) &= \frac{\sin\alpha}{\sqrt{2(1-i_o)(1-\cos\alpha)+i_o^2}}
\end{aligned}
\right\} \qquad (277)
$$

To integrate equations (274), Matespuro and Guskov first used Saakyan's soil values which were measured by means of a penetrometer with a flat plate of diameter d (see equation 16):

$$\sigma = k_S \left(\frac{z}{d}\right)^n \qquad (278)$$

However, following the previously mentioned practice, they modified the vertical plate sinkage vector and deviated it from the normal by angle $\sigma/2 + \theta$. Hence they assumed that plate sinkage z corresponds to track sinkage z_x, with the following transformation:

$$z_x = z/\cos(\alpha/2 + \theta) \qquad (279)$$

Substituting in equation (274), (276), (278), and (279) Matespuro and Guskov obtained:

$$R_t = \int_0^{z_o} k_S b \, \frac{(\cos \alpha/2 + \theta)}{\sin\alpha} \left[\frac{z}{d\cos(\alpha/2 + \theta)}\right]^n dz \qquad (280)$$

but (see equations (278) and 279):

$$\frac{\sigma}{k_S} = \left[z_o/d\cos(\alpha/2 + \theta)\right]^n \qquad (281)$$

Thus, upon substituting equation (281) in (280), and integrating, equation (280) yields:

$$R_t = \frac{b\cos(\alpha/2 + \theta)}{\sin\alpha} \, \frac{\sigma z_o}{1 + n} \qquad (282)$$

Now, Matsepuro and Guskov assumed that:

$$\sigma = p = W/2b\,\ell' \tag{283}$$

and that the nominal value of track length ℓ' of the frontal track portion normal to the vector of the absolute speed v_o (Figure 49) equals:

$$\ell' = \ell \cos(\alpha/2 + \theta) = \frac{z_o}{\sin\alpha} \cos(\alpha/2 + \theta) \tag{284}$$

Another assumption was that the loading area of the track portion thus conceived equals the loading area of the penetrometer plate, i.e.;

$$\pi d^2/4 = b\,\ell \tag{285}$$

Thus, from equations (284) and (285)

$$\pi d^2/4 = [b z_o \cos(\alpha/2 + \theta)]/\sin\alpha \tag{286}$$

However from equation (281):

$$d = \frac{z_o}{(\sigma/k_s)^{1/n} \cos(\alpha/2 - \theta)} \tag{287}$$

Combining equations (286) and (287) and solving the result for z_o yields:

$$z_o = \left[\frac{\sigma}{k_s}\right]^{2/n} \frac{4b}{\pi \sin\alpha} \cos(\alpha/2 + \theta) \cos^2(\alpha/2 - \theta) \tag{288}$$

and after substituting equation (288) in equation (282):

$$R_t = \frac{4b^2 p^{(n+2)/n} \cos(\alpha/2 + \theta) \cos^2(\alpha/2 - \theta)}{\pi k_s^{2/n} (1 + n) \sin^2\alpha} \tag{289}$$

Since motion resistance R is:

$$R = R_t \sin\alpha/\cos(\alpha/2 + \theta) \tag{290}$$

combining equations (289) and (290) gives for two tracks:

$$R = \frac{8b^2 p^{(n+2)/n} \cos(\alpha/2 + \theta) \cos(\alpha/2 - \theta)}{\pi k_s^{2/n} (1 + n) \sin\alpha} \tag{291}$$

Upon substituting in equation (291) and equations (277) the authors proposed the following final formula:

$$R = \frac{8b^2 \sin^2 \alpha}{\pi} \quad \frac{1 - i_o}{\left[2(1-i_o)(1-\cos\alpha)-i_o^2\right]^{3/2}} \quad \frac{p^{(2n+2)/n}}{k_S^{2/n}(1+n)} \tag{292}$$

This formula defines R for a track moving without trim. How much better results were obtained with equation (292) than with Antonov and Bekker's equations (273) and (272) which do not include slip, remains to be seen: Matsepuro and Guskov did not report any comparison, even at $i_o = 0$.

It is obvious, however, that the character of assumptions and mathematics used by the authors in the "translation" of soil values from the penetrometer plate to the track may not have produced better accuracy of prediction than that obtained with simple Bernstein-Letoshnev-Bekker calculations for maximum slip. But the important methodological improvement due to the inclusion of slip i_o, which was excluded from the other equations, cannot be overlooked.

As if the authors were aware of some inefficiency of equation (292), they went through the same mathematics again, assuming this time, Korchunov-Housel soil value system (see equation 17) instead of Saakyan systems:

$$p = p_{KO}\left[1 - e^{-z/k_{KO}}\right] \tag{293}$$

Thus, soil reaction expressed by equation (274) was:

$$R_t = \int_A \sigma \, dA = \int_A p_{KO}\left[1 - e^{-zk_{KO}}\right] dA \tag{294}$$

The final solution of integral (294) and the subsequent transformations of R_t into R yielded the following equation for the motion resistance of two tracks:

$$R = 2bk_{KO}p_{KO}\left\{\frac{\sin\alpha}{\sqrt{(1-i_o)^2 - 2(1-i_o)\cos\alpha + 1}} \times\left[(1-p/p_{KO})\sqrt{(1-i_o)^2-2(1-i_o)\cos\alpha+1/\sin\alpha}_{-1}\right] - \ell_n(1-p/p_{KO})\right\} \tag{295}$$

Comparison of equations (292) and (295) alone hints at the worrisome complexity of Saakyan and Korchunov soil values. Apparently Korchunov himself had that feeling, since he proposed a simpler solution of equation (295). Unfortunately, that solution as reported by Matsepuro and Guskov appears to be incomplete, and will not be discussed further, although it suggests that Matsepuro and Guskov were not alone when theorizing on motion resistance of tracks.

In any case, the review of work on track performance executed by the Minsk school around 1961 shows that the impact of American work stirred much activity. The Russians naturally tended to preserve the original and to foster the new Russian achievements. The practical success went further than in the United States, since it encompassed the track slip in the motion resistance equations without complex computerization. Most of these equations also were adapted to parametric evaluation of track-soil performance, and their solutions were produced in the form of alignment charts. Apparently, computers were scarce around 1960.

In all this work the Minsk school displayed the same methodological treatment of the problem as that by the Land Locomotion Laboratory in Detroit. The absence of arbitrary empirics was striking and significant.

The problem of track slip attracted much attention by Russian investigators. A Professor Opeiko (1961), for example, produced and published under the auspices of the Minsk school a complex expression which will not be deduced here, since it probably has only a historical significance. The final slip equation, however, is quoted below because it shows the method of approach to the problem:

$$i_o = 2\sqrt{2K_o}\ \frac{E\ P}{K_o W}\sqrt{\frac{1 + \sqrt{1 + (K_o^2\ W^2/E^2 P^2)\ (1 + N/2)^2}}{1 + N/2}} \qquad (296)$$

where k_o is a coefficient of horizontal soil shear, and K_o is the modulus of that shear (definitions are lacking). E is Young's modulus; W is vehicle weight and P, the shearing force exercised by the track. N is the number of passes.

Opeiko's radical departure from any previous practice indicates that much diverse speculation on track performance was encouraged, even in Minsk in the early ninetten sixties. He himself performed numerous calculations and analyses, using as parameters

$k_o = 0.05$ and the ratio $K_o/E = 1/3$. Other cases of computations included $E = 50,000$ kg/m^2, $K_o = 12,500$ kg/m^2, and $k_o = 0.07$ (dimensionless).

However, right in the next chapter following Opeiko's conjectures, Professor Matsepuro and Dr. Yanushkevich (1961) did not refer to anything similar, as if they were admonishing Professor Opeiko for his Young modulus and two extra soil values extravaganza, apparently never used before. As if to make it absolutely clear, Matsepuro and Yanushkevich recalled reference (Bekker, 1956), and stated that in frictional and turf soils (i. e., soils where Young modulus is applicable for small deformations) the pulling force P equals to $W\tan\varphi$ where φ is the angle of friction. They also seem to have reminded Opeiko that in cohesive soils: $P = Ac$. Thus they reformulated Coulomb's equation:

$$P = W\tan\varphi + Ac$$

This rather close following of American work was pictorially illustrated by Figure 51. Further reporting of the state of the art included references to the Russian soil value system such as that by Professor Pokrovskii (equation (21)) and N. A. Nasiedkin (details lacking). Nevertheless, the fashion in which both chapters (by Opeiko and Matsepuro-Yanushkevich) were put together indicates that the Minsk school tried to educate the Russian audience before displaying any "commonality" with the American school, at least from methodological viewpoint.

That school was again popularized with the translation by Frenkin (1962) of the series of articles published in Machine Design by Bekker (1959-1960). At the same time, Matsepuro and Hao-Sin-Fan (1962) further followed their line of thought in an apparent contest with Opeiko (1962), who in turn published more of his approach.

Matsepuro and Hao-Sin-Fan adhered to their 1961 reasoning with diligence, though not without change. Incidentally, they changed most of their previous denotations, which made the task of the present writer unduly complex. Their solutions also became more involved because they considered a track moving not in the horizontal position, (Figure 50), but in a trimmed position. This would have added more angles to the angle of approach α and to the "slip angle" θ, further complicating the issue. However, θ was dropped; "no slip" made it more manageable.

т. е. изменение соотношения длины и ширины гусеницы не должно повышать трудоемкость изготовления, металлоемкость и капитальные вложения при освоении производства машины. Габариты трак-

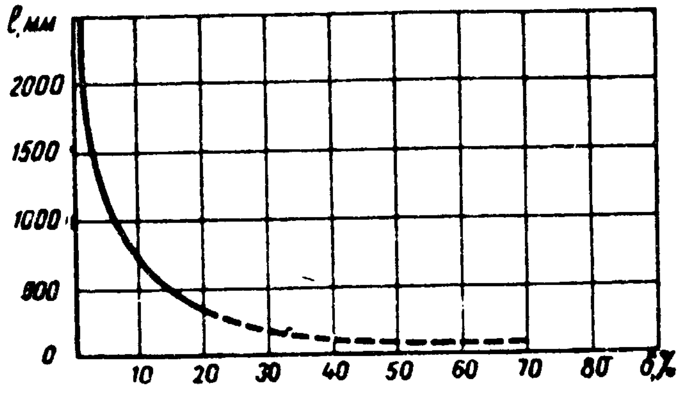


Рис. 128. Зависимость между буксованием и длиной опорной поверхности гусеницы (по Bekker'y M. G.).

Figure 51 Reproduction of p 219, Vol. VIII of "Voprosy..." (1962) Showing a Search For Optimum Track Length and Minimum Slip With a Reference To An American Work.

In this work, soil values for turf type of the ground were assumed in accordance with Korchunov (equation 293); for compressive ground, Bernstein-Letoshnev equation $p = kz^n$ was used. Surprisingly, as mentioned before, the slip was not considered. The mathematics related to the derivation of equations was similar to that reported previously. For Korchunov soil values p_{KO} and k_{KA}, the coefficient of motion resistance, $f = R/W$, of the tractor was defined

$$f = \frac{2\,p_{KO}b}{W} \tan(\alpha + \beta) \left[\ell'' - \frac{k_{KO}}{A^o} \left(1 - e^{-\ell'' A^o / k_{KO}} \right) \right] + \frac{2\,p_{KO}b}{W} \tan\beta \left[\ell_g \cos\beta - \frac{k_{KO}}{B'} \left(e^{-\ell'' A^o / k_{KO}} - e^{-(\ell_g \cos\beta + \ell'' A)/k_{KO}} \right) \right] \quad (297)$$

In this equation, α was the angle of approach of the track, and β the angle of track trim; ℓ'' was a horizontal projection of the "approach portion" of the track length ℓ (compare Figure 49); A^o was expressed by equation, including soil friction angle φ:

$$A^o = \frac{\tan(\alpha + \beta)}{\cos(\alpha + \beta - \varphi)} \quad (298)$$

ℓ_g was the length of the track ground contact area, excluding the "approach portion": B' was defined by equation:

$$B' = \frac{\tan\beta}{\cos(\beta - \varphi)} \quad (299)$$

The differences in basic assumptions between equations (292), (295), and (297) were thus rather involved:

Equation	Soil Values	Track Trim	Slip
(292)	Saakyan	no	yes
(295)	Korchunov	no	no
(297)	Korchunov	yes	no

and indicate the existence of much search for a practical solution. The composition of the soil value system in equation (297) was significant (p_{KO}, k_{KO}, and φ). No slip was included, which seems to suggest that this work may have preceded the work leading to equations (292) and (295). Under these circumstances the rationale of the solutions, equations (292), (295), and (297), may be seen only in the desire of the Minsk school to preserve the originality and to try to do more, perhaps, under the impact of the American school.

The influence of the latter was not hidden in the formula which expressed the coefficient of adhesion, μ_a, between the track and the ground, in terms of Coulombian τ_{max} and the corresponding optimum soil deformation j_{opt} introduced by Bekker (1956):*

$$\mu_a = \frac{k}{B'}\sqrt{2/Wp\lambda}\,[B'\sqrt{A\lambda}\cos\beta - \ell''A^o)^{n+1} - (\ell''A^o)^{n+1}]\tan\varphi$$
$$+ i_o h \frac{\tau_{max}}{j_{opt}} \sqrt{2/Wp\lambda}\,[A\lambda/2s_t) + \sqrt{A\lambda/2}]\,[(2\sqrt{A\lambda}/3s_t) + (1/3)]\,\xi\cos\beta \tag{300}$$

In equation (300), Bernstein-Letoshnev soil values k and n were used. A^o and B' were defined by equations (298) and (299). λ was the ratio of track length to width: $\lambda = \ell/b$; A was the ground contact area: $A = \ell b$; h was grouser height and s_t, track-link length; and ξ was an empirical "correction" factor (not quite specified, except for information that $\xi < 1$).

The involved deductive path and the complexity of equation (300) suggest that it could not have been too satisfactory, and the introduction of the "correction" factor ξ proves the point. Nevertheless, the merit of this solution lies in its attempt to defining track pull as a function of track design parameters and soil properties. This achievement would have been impossible when using "cone index."

Equations (297) and (300) were apparently tested in the field and in the laboratory. Although test equipment, soil measuring instrument (Figure 19), and test results were described in detail, no direct comparison between theoretical prediction and empirical data was made.

This rather enormous effort, backed by complex computing and slightly sophisticated theorizing, seems to imply a rather frantic search for f and μ_a, and their structure. To illustrate this point it may suffice to mention that another equation proposed by Matsepuro and Mao-Sin-Fan for f was composed of 15 members, two of which were expressed by separate equations.

* In this case Matsepuro and Hao-Sin-Fan even used American denotation j instead of previously used denotation S or δx.

The fact that the Minsk school was closely watching American work, which also expressed traction of a vehicle in terms of design soil properties, and slip, is illustrated by Figure 52a and 52b.

As previously mentioned, Professor Opeiko (1962) followed his rather unorthodox way in another chapter. Apparently he wanted to develop something more general than Matsepuro, Hao-Sin-Fan, and Yanushevich, for he considered that soil thrust and vehicle adhesion must overcome the following forces of moving a vehicle:

- gravity force (slope?)
- trailer hauling force
- forces of inertia
- soil deformation force, which "does not include motion resistance disappearing as a result of multiple loading by the (consecutive) passage of bogie wheels
- soil deformation in traversing the catenary track humps between wheels.

Whatever the meaning was of all these postulates, it led to the introduction of numerous "ad hoc" coefficients and hypotheses. Grandoise mathematics with partial differential equations and complex integrals was an unmistakable sign of an academic exercise. All were based on Young's modulus of soil deformation. Opeiko['s wo]rk stood thus in sharp contrast to works by all the other authors published in the [sam]e volume. The conclusions he reached upon performing numerical calculations indicated that the Professor was a layman in land locomotion, though expert in theoretical mechanics. For he would not have concluded that in accordance with his theory the improvement of mobility of a tracked tractor may "require automatic regulation of the location of the center of track load, which could be performed by reducing length of the ground contact area through lifting the front wheels..." How many similar projects were undertaken in the United States only a few realize.

It is not surprising that the present writer did not see more publications by Opeiko.* For Russian engineers are more down to earth than anyone else, including their American and Canadian colleagues who still have great patience in listening to the

* There was another paper briefly mentioned in "Voprosy..." (1964), which was written in 1960.

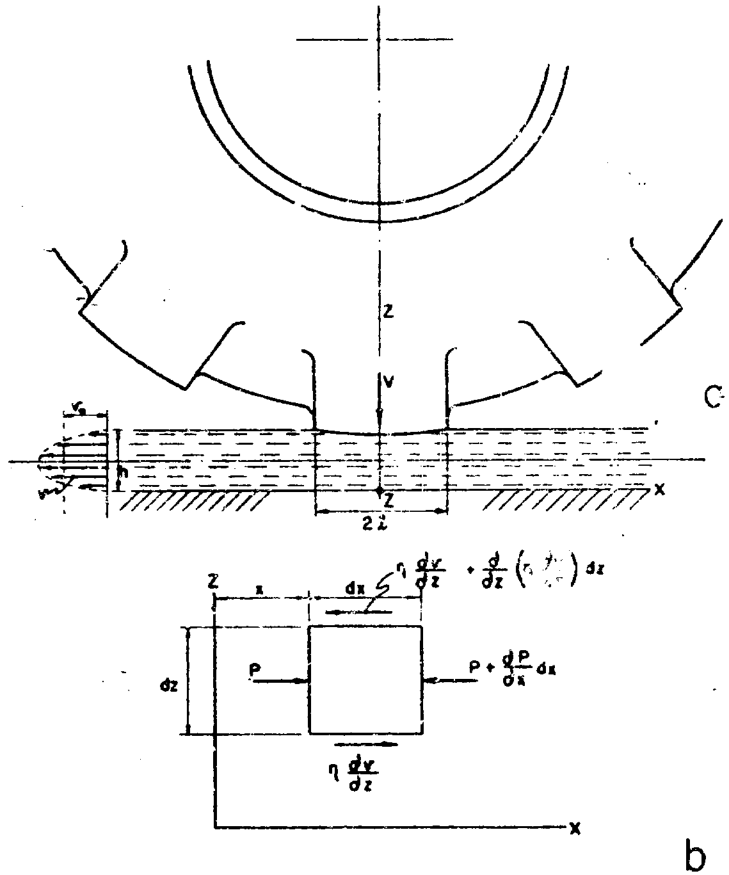


Fig. 100

dimensional case, the equilibrium of the forces acting upon an elementary prism (Figure 100b) in the direction of the xx axis will be as follows:

$$-\eta \frac{\partial v}{\partial z} dx - \eta \frac{\partial^2 v}{\partial z^2} dz\,dx + \eta \frac{\partial v}{\partial z} dx + p\,dz - p\,dz - \frac{\partial p}{\partial x} dx\,dz = 0$$

or, when simplified,

$$\frac{\partial p}{\partial x} + \eta \frac{\partial^2 v}{\partial z^2} = 0\,, \tag{227}$$

where p = unit load acting upon a given area, v = speed of flow of the fluid particle, and η = viscosity of the fluid covering the road.[100]

Integrating equation (227) gives

$$\frac{\partial v}{\partial z} = -\frac{1}{\eta}\frac{\partial p}{\partial x} z + c_1$$

and

$$v = -\left(\frac{1}{2\eta}\frac{\partial p}{\partial x} z^2 + c_1 z + c_2\right).$$

Since $v = 0$ for $z = 0$ and for $z = h$, then $c_2 = 0$ and

$$\frac{1}{2\eta}\frac{\partial p}{\partial x} h^2 + c_1 h = 0\,.$$

Thus

$$c_1 = -\frac{1}{2\eta}\frac{\partial p}{\partial x} h\,.$$

And finally,

$$v = \frac{z}{2\eta}\frac{\partial p}{\partial x}(h - z)\,. \tag{228}$$

The average speed of fluid particle[illegible] may be found from the following equation (Figure 10[illegible]

$$v_0 = \frac{1}{h}\int_0^h v\,dz = \frac{1}{2\eta}\frac{\partial p}{\partial x}\frac{1}{h}\int_0^h (zh - z^2)\,dz = \frac{1}{\eta}\frac{\partial p}{\partial x}\frac{h^2}{12}\,. \tag{229}$$

Assume that the pressure acting upon the fluid causes a reduction of h by dh. Thus the volume of fluid squeezed out between 0 and x is $x\,dh$. For an incompressible fluid, this volume equals $h\,dx$. Hence,

$$x\,dh = h\,dx$$

or

$$\frac{dh}{dt} x = \frac{dx}{dt} h\,.$$

Figure 52a Bekker's (1956) original referred to by Matsepuro and Yanushkevich (1961). See Figure 52b.

Соответственно

$$P_f' = f_1 G_1.$$

Это окажется целесообразным, если

$$P_к' - P_к > P_f' - P_f$$

или

$$G_1 \operatorname{tg} \rho_1 + c_1 S_1 - G \operatorname{tg} \rho - c S > f_1 G_1 - f G,$$

откуда

$$G_1 (\operatorname{tg} \rho_1 - f_1) - G (\operatorname{tg} \rho - f) + c_1 S_1 - c S > 0.$$

Если увеличение осадки достигается только за счет изменения опорной поверхности ходового аппарата (при $G = \mathrm{const}$), то неравенство упрощается и принимает вид:

$$G(\operatorname{tg} \rho_1 - \operatorname{tg} \rho - f_1 + f) + c_1 S_1 - c S > 0,$$

$$\operatorname{tg} \rho_1 - \operatorname{tg} \rho + \frac{c_1}{q_1} - \frac{c}{q} - f_1 + f > 0,$$

где

$$q_1 = \frac{G}{S_1} \text{ и } q = \frac{G}{S}.$$

В случае изменения нагрузки на ходовой аппарат (при $S = \mathrm{const}$) для обеспечения повышения проходимости машины должно соблюдаться неравенство

$$G_1 (\operatorname{tg} \rho_1 - f_1) - G (\operatorname{tg} \rho - f) + S (c_1 - c) > 0.$$

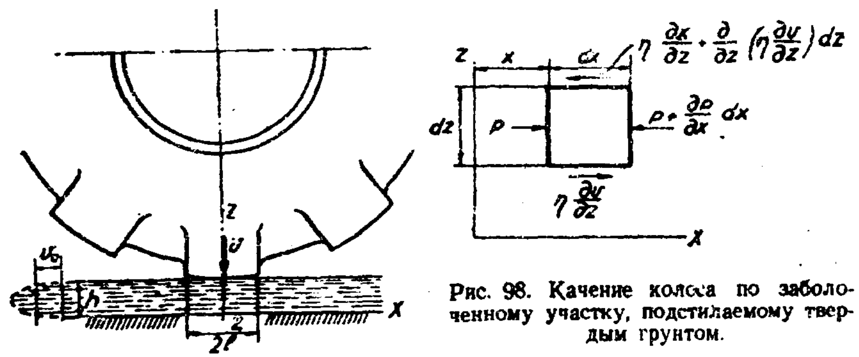


Рис. 98. Качение колеса по заболоченному участку, подстилаемому твердым грунтом.

Проходимость заболоченных участков в значительной степени зависит также от свойств разжиженного слоя грунта, его толщины, от конструктивных и эксплуатационных параметров машины.

Действительно, если глубина верхнего разжиженного слоя $h_ж$ (рис. 98), то в случае рассмотрения плоской задачи

$$\eta \frac{\partial v}{\partial z} dx - \eta \frac{\partial^2 v}{\partial z^2} dz\, dx + \eta \frac{\partial v}{\partial z} dx + p dz - p dz - \frac{\partial p}{\partial x} dx\, dz = 0$$

или

$$\frac{\partial p}{\partial x} + \eta \frac{\partial^2 v}{\partial z^2} = 0,$$

где

p — удельная нагрузка на данную площадь;
v — скорость движения жидкости;
η — вязкость жидкости.

После интегрирования этого уравнения получим

$$\frac{\partial v}{z} = -\frac{1}{\eta} \frac{\partial p}{\partial x} z + c$$

и

$$v = -\frac{1}{2\eta} \frac{\partial p}{\partial x} z^2 - C_1 z - C_2.$$

При $z = 0$ и $z = h$ $v = 0$.
В этих случаях $C_2 = 0$

и

$$\frac{1}{2\eta} \frac{\partial p}{\partial x} h^2 + C_1 h = 0.$$

Следовательно,

$$C_1 = -\frac{1}{2\eta} \frac{\partial p}{\partial x} h.$$

Окончательно

$$v = \frac{z}{2\eta} \frac{\partial p}{\partial x} (h - z).$$

Среднюю скорость движения частицы жидкости $v_{ср}$ можно получить из уравнения

$$v_{ср.} = \frac{1}{h} \int_0^h v\, dz = \frac{1}{2\eta} \frac{\partial p}{\partial x} \cdot \frac{1}{h} \int_0^h (zh - z^2)\, dz = \frac{1}{\eta} \frac{\partial p}{\partial x} \frac{h^2}{12}.$$

Если принять, что при воздействии колеса на жидкость ее высота h уменьшается на dh, то вытесненный объем составит $x dh$. Поскольку жидкость несжимаема,

$$x dh = h dx$$

или

$$\frac{dh}{dt} x = \frac{dx}{dt} h,$$

но

$$\frac{dx}{dt} = v_{ср}.$$

Следовательно,

$$\frac{dh}{dt} = \frac{h}{x} v_{ср}.$$

В таком случае

$$\frac{\partial p}{\partial x} = \eta \frac{dh}{dt} \frac{12x}{h^3}.$$

При интегрировании получим

$$p = \eta \frac{dh}{dt} \frac{6x^2}{h^3}.$$

Figure 52b Matsepuro and Yanushevich (1961) original referred Bekker (1956). See Figure 52a.

abstracts of the Academe, and simultaneously forging their way ahead with crude empirics, although applied mechanics and mid-road systems analysis are cheaper and faster.

Skotnikov (1963) of the Minsk school showed this truism in action in his interesting article on off-road mobility of tracked tractors. His work, performed under the auspices of Minsk school, was methodologically close to Matsepuro et al.; it was divorced from Opeiko's theories. Skotnikov also borrowed from reference (Bekker, 1956) not only the method of evaluation of load distribution under the catenaries of the track, but also some of the denotations (such as track sag: $s_o - s$).

His original contribution consisted of introducing a chain track with pitch s_t instead of a continuous track band considered by Bekker. As he was exclusively concerned with turf soils he used the Young modulus and the Poisson ratio, which was perfectly all right for small allowable deformations. These soil values were, however, supplemented with Housel-Korchunov (equation (18)) values A_o and B_o, as well as with other values which he introduced without much explanation. For instance, track sinkage in deep turf layer was determined by equation:

$$z = \frac{1}{k_{KO}} \ell n (1 - p/p_{KO}) \tag{301}$$

where k_{KO} and p_{KO} were explained in equation (17). Sinkage in two-layer turf or hard ground:

$$z = \frac{1}{p_{KO}} \frac{A}{U} p \tag{302}$$

Equation (302) is similar in structure to the equation developed much later in the United States (Bekker, 1969). In this respect Skotnikov's work is another example of Russian diligence of developing what we have left idling.

When adapting catenary load equations from reference (Bekker, 1956), Skotnikov also used the Bernstein-Letoshnev formula $p = kz^{n=1}$, assuming however that in case of turf, $k = k_{SK}$, where k_{SK} was explained in equation (45). By considering a chain of track plates instead of a continuous band, Skotnikov deduced the following equation for the load acting upon one catenary of the track along distance x measured from the centerline of the catenary (for details compare Bekker, 1956):

$$W_t = 2bk_{SK}x\,[(W_w/bs_t) - 1.23\sqrt{s(s_o - s)}\,(1 - 0.33x^2/s^2)\,] \qquad (303)$$

and for the complete catenary (x = s):

$$0.82\,k_{SK}\sqrt{s(s_o - s)} = (W_w/bs_t) - W_t/2bs) \qquad (304)$$

where W_t is the track load; W_w is wheel load; s_t is track pitch; s_c is half-track length between two wheels; and s is distance between the centerline of the catenary and the end of the track shoe, which is symmetrically located beneath the wheel.

Experimental and theoretical study of equations (303) and (304) led, among others, to the conclusion that if wheel distance ℓ and track pitch s_t are related by inequity:

$$\ell/s_t \leq 1.7 \qquad (305)$$

the whole track must be considered as a rigid plate. Much useful discussion of practical significance followed. The writer dwelt on static and dynamic, short and long duration loading of turf in one and in multi-pass operations. He quoted several references by other Russian investigators covering the period of 1955 to 1959, and deduced practical criteria for tracked vehicle mobility over turf.

Basically he formulated three such criteria: (1) the rupture pressure defined by the Housel-Korchunov area-perimeter ratio; (2) the pressure defined by allowable sinkage within elastic range; and (3) the pressure defined by vegetation shear due to slip:

$$\begin{aligned} &(1) \quad p = f(A_o + B_o\,A/U) \\ &(2) \quad p = f(z) \qquad\qquad (306) \\ &(3) \quad p = f(i_o) \end{aligned}$$

Skotnikov's work based on American work, though half theoretical and half empirical, went beyond the scope of what has been done in the United States. We have not matched as yet the attempt by the Minsk school to master transportation problems over the organic soils, and we still employ "hit and miss" practice in the tundra of the North Slope, among others.

Fast growing interest of Russian engineers in track-soil relationship was further demonstrated in the paper by Lebedev and Sidorov (1965). Since they investigated a

turning vehicle they derived equations of forces acting upon the ground, and then deduced the ground stresses. Soil characteristics were not specifically included. It was the vehicle input into the ground that was investigated, rather than the safe input of load bearing capacity of the ground into the vehicle.

It was significant that Guskov (1964), writing almost at the same time in "Voprosy... ", Vol. XIII, dwelt on the Katsygin soil value system (equation (29)) and reported vehicle soil thrust in equation:

$$H = 2b \int_0^{\ell} \tau_x (dx) \tag{307}$$

which is identical to the equation originally proposed by Bekker (1956). By introducing Katsygin soil parameters, however, he obtained:

$$H = 2b \int_0^{\ell} \mu_m p \left[1 + \frac{\mu_{KA}}{\cosh \frac{i_o x}{k_\tau}} \right] \tanh \frac{i_o x}{k_\tau} \, dx \tag{308}$$

and upon integration

$$H = \frac{2b\mu_m p k_\tau}{i_o} \left[\ell n \cosh \frac{i_o \ell}{k_\tau} - \mu_{KA} \left(\frac{1}{\cosh i_o \ell / k_\tau} - 1 \right) \right] \tag{309}$$

Considering that $\mu_a = H/b\ell p$, where $b\ell p = W/2$, equation (307) may be directly compared with equation (300). The simplicity of formula (209) and of the Katsygin soil value system is obvious. This may have been the reason that equations (292), (295), and (300) were not often referred to in parametric vehicle evaluations. Instead, equations based on Katsygin soil values were elaborated more.

An example of such elaboration was given, for instance, in the definition of the optimum vehicle slip; from equation (309), by defining conditions for

$$\frac{\partial H}{\partial i_o} = \frac{\mu_m W}{i_o} \tanh \frac{i_o \ell}{k_\tau} - \frac{\mu_m k_\tau W}{\ell} \ell n \cosh \frac{i_o \ell}{k_\tau} + \frac{\mu_{KA} \mu_m k_\tau W}{i_o \cosh (i_o \ell / k_\tau)} \times \left[\cosh \frac{i_o \ell}{k_\tau} - \frac{i_o \ell}{k_\tau} \cosh \frac{i_o \ell}{k_\tau} \right] - \frac{\mu_{KA} \mu_m k_\tau W}{i_o^2} = 0 \tag{310}$$

Solution of equation (308) gives i_o-optimum for various design and soil parameters.

Further elaboration of this technique is seen in the development of an equation for ground pressure P_x which affects thrust H under the influence of the drawbar pull DP (Figure 53):

$$p_x = (p/\ell)\,[\ell + 6s + 6DPh/W] - (\chi_G\, 2p/\ell)\,[6s - 6DPh/W] \qquad (311)$$

where χ_G is the displacement of the center of pressure of the track with reference to the center of the ground contact area. DP is drawbar pull. Under these circumstances Guskov deduced the following equation for soil thrust:

$$H = (2b\mu_m k_\tau p/i_o\ell)(\ell \pm 6s \pm 6\,DPh/W)\left[\ln\cosh\frac{i_o\ell}{k_\tau} - \mu_{KA}\left(1/\cosh\frac{i_o\ell}{k_\tau} - 1\right)\right] \pm (4b\mu_m p/\ell^2)(\pm 6s \pm 6\,DPh/W) \qquad (312)$$

$$\times\left[(\mu_{KA}\, k_\tau/i_o\left(\frac{2k_\tau}{i_o}\tan^{-1}\epsilon^{i_o\ell/k_\tau} - \frac{\pi k_\tau}{2i_o} - \ell/\cosh\frac{i_o\ell}{k_\tau}\right)\right]$$

These developments are most significant. For, with the exception of work by Reece (1965) in England, and some attempts in this country (Bekker, 1969), we still lack a solution comparable in scope to Guskov's solution (equation (312)).

Since in this area our method is identical to the Russian method, the present writer sees a challenge to American research: why not try to develop equation (312) by replacing Katsygin soil values with Bekker or Reece soil values? Check experimentally which solution will be cheaper, simpler, and more accurate. Would it not be desirable to catch up with the Russians, and if not, use their solution, should it be found reliable?

Guskov's work has been steadily gaining in significance. His book on optimization of tractor parameters was published in 1966 on the basis of his cooperation with TsNIIMESH, NATI-NAMI and VIM Institutes.

The book dwells first on track kinematics, which is of no particular interest in this report. It refers to American literature (Bekker, 1955 and 1956), two British, and

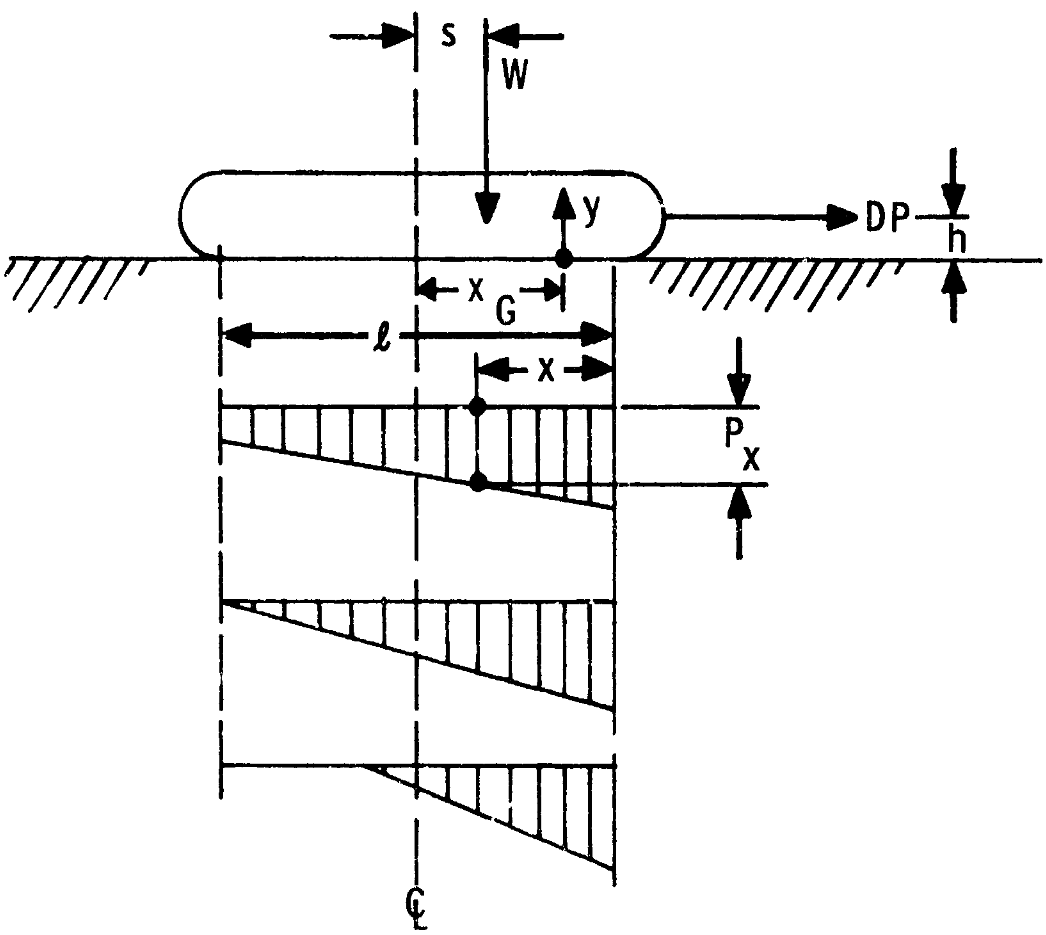


Figure 53 Ground Pressure Displacement Due To The "Shifting" of CG.

three German papers. In this context it reviews, among others, the elastic band-track catenary, assuming again $p = kz$. However, there is a distinction between Guskov and Bekker catenaries: Bekker used exponential functions while Guskov applied their equivalent, the geometrical hyperbolic functions. This makes it obvious that the American and Russian soil-track (and wheel) mechanics are practically the same, for the differences are expressed by the form, rather than by content.

This conclusion also was proved by Skotnikov's (1963) treatment of load distribution under the track catenary. Note, however, that Skotnikov used Korchunov soil values (turf) while Guskov used Letoshnev's. Thus, according to Guskov track sinkage in the middle of the catenary:

$$z = W_t/2\sqrt{kbH_0/2}\ \left(e^{\ell/2\sqrt{2kb/H_0}} - 1\right) \qquad (313)$$

The catenary formula by Skotnikov was expressed by Equation 304).

Though not entirely original, Guskov's (1966) book brought a distinct and new improvement in track performance – design evaluation. Besides discussing mechanical, internal track motion resistance (which is beyond the scope of this report) he introduced the analysis of the track in trimmed position. Motion resistance was defined with slip, similar to equations (292) and (295). Traction equations also included slip (as it does in the American approach). In addition, Guskov made a clear distinction between "organic" and "mineral" soils by applying to each different soil value system. This distinction was made in the United States somewhat later, within broad interpretation of Bevameter techniques (Bekker, 1969). Obviously, we learned something from the Russians as they started advancing beyond our state of the art.

According to Guskov, "mineral soils" are measured in Katsygin values equation (24); "organic soil," in Korchunov values equation (17).

The novel treatment of the track resistance included not only the "frontal resistance," which was deduced in the same manner as shown in equation (292), but also the "rut making" under the flat trimmed track portion. This, as far as it is known, was the first complete treatment of the problem, besides the simplified American approach to bulldozing and compaction resistance (Bekker, 1956).

Figure 54 shows a general plan of f- :ce geometry. Motion resistance of the tracked vehicle is composed of two elements:

- R_1 – acting upon "approach" track portion AB
- R_2 – acting upon bearing track portion BC

which were defined separately.

The deduction of R_1 followed the same method that led to equation (292). However, since in this case different soil values were used, a different form of equation (292) was obtained.

Thus, Guskov started again with equations (274) and (276):

$$R_t = \int_A \sigma \, dA = \int_0^z \frac{\sigma \, b \cos(\alpha/2 + \theta)}{\sin \alpha} \, dz \tag{314}$$

and (see equation (290)):

$$R_1 = \frac{R_t \sin \alpha}{\cos (\alpha/2 + \theta)} = \frac{\sin \alpha}{\cos (\alpha/2 + \theta)} \int_0^z \frac{\sigma b \cos (\alpha/2 + \theta)}{\sin \alpha} \, dz \tag{315}$$

Assuming Katsygin soil values, equation (24):

$$\sigma = p_{KA} \tanh (k_{KA}/p_{KA} 0) z' \tag{316}$$

and considering that (see equation 279):

$$z' = z/\cos (\alpha/2 - \theta) \tag{317}$$

Guskov substituted equations (316), (317), (277), and (318), in equation (315), equation (318) being a transformation of equation (316):

$$z' = (p_{KA}/k_{KA}) \tanh^{-1} (p/p_{KA}) \tag{318}$$

Upon integration of equation (315) he obtained:

$$R_1^{\text{min. soil}} = \frac{2bp^2_{KA} \eta_s}{k_{KA}} \ln \cosh \frac{W}{2b \, p_{KA} \eta_s} \tag{319}$$

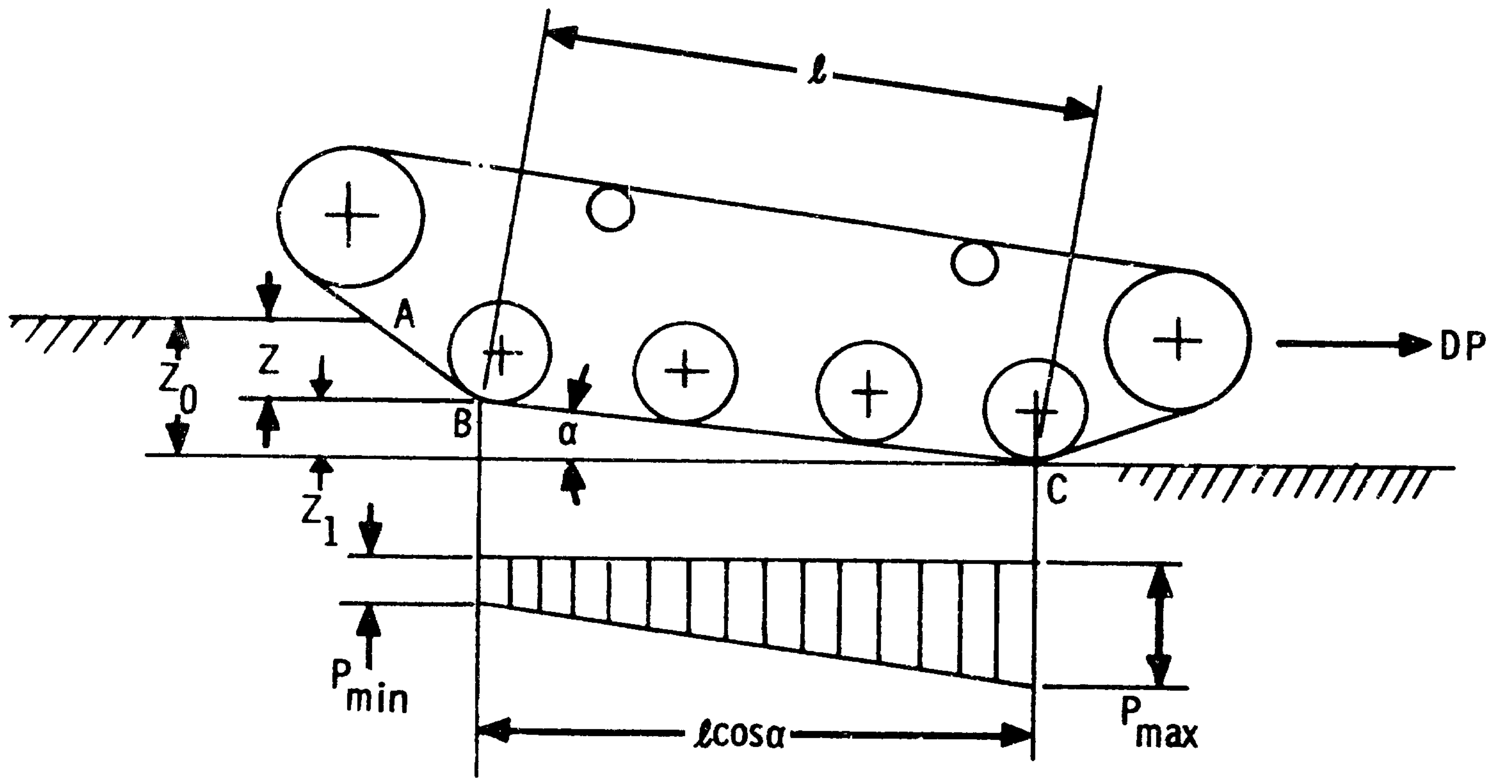


Figure 54 Guskov's (1966) force-geometry plan for a tracked vehicle

where η_s:

$$\eta_s = \frac{\sin \sigma}{\sqrt{(v_A/v_T)^2 - (2v_A/v_T \cos \alpha) + 1}} \tag{320}$$

Since $1 - v_A/v_T = i_o$, equation (320) may be written as follows:

$$\eta_s = \frac{\sin \alpha}{\sqrt{(1 - i_o)^2 - 2(1 - i_o) \cos \alpha + 1}} \tag{321}$$

For organic soils, the R_1 equation looked different, because Korchunov values were used:

$$\sigma = p_{KO} \left[1 - e^{-z/k_{KO}} \right] \tag{322}$$

Including equation (322) and following the same procedure, Guskov obtained equation (295), as was reported before. At this time, however, he substituted ground pressure $p = W/2b\ell$ with vehicle weight W and shortened the final expression by eliminating i_o and using η_s of equation (321):

$$R_1^{\text{org. soil}} = 2bk_{KO}p_{KO} \left\{ \eta_s \left[(1 - W/2b\ell p_{KO})^{1/\eta_s} - 1 \right] - \ell n(1 - W/2b\ell p_{KO}) \right\} \tag{323}$$

Motion resistance R_2 due to soil compaction under track segment BC (Figure 54) was evaluated next. Assuming that it was caused by the nonuniform load distribution, the latter was expressed as the difference between p_{max} and p_{min} (Figure 54):

$$\Delta p = p_{max} - p_{min} \tag{324}$$

Elementary track loading area dA is:

$$dA = b \cot \alpha \, dz_o \tag{325}$$

and,

$$\alpha = \sin^{-1}(z_1/\ell) \tag{326}$$

If the vehicle moved by distance ds, the elementary work of the track was:

$$dE_o = R_t\, dz_1 \tag{327}$$

where R_t is ground reaction acting upon segment BC. But, as stated before, considering equation (325):

$$R_t = \int_A \sigma\, dA = \int_o^{z_1} \sigma\, b \cot\alpha\, dz_1 \tag{328}$$

Also, $$dE_o = R_2\, ds \tag{329}$$

and with equation (327)

$$dE_o = R_2\, ds = R_t\, dz_1 \tag{330}$$

Hence,

$$R_2 = R_t \frac{dz_1}{ds} \tag{331}$$

where,

$$dz_1 = ds \tan\alpha \tag{332}$$

Accordingly, following further Guskov's line of reasoning and equations (331) and (332):

$$R_2 = R_t \tan\alpha = \int_o^{z_1} \sigma b \cot\alpha\, dz_1 = \int_o^{z_1} \sigma b\, ds \tag{333}$$

Upon substituting Katsygin soil values and equations (332) and (326) in equation (333), the integration yields:

$$R_2^{\text{min. soil}} = (2bp^2_{KA}/k_{KA})\, \ln \cosh(\Delta p/p_{KA}) \tag{334}$$

and for Korchunov soil values, equation (322):

$$R_2^{\text{org. soil}} = 2bk_{KO}p_{KO}\left[-\ln(1 - \Delta p/p_{KO}) - p/p_{KO}\right] \tag{335}$$

The total track motion resistance R was then obtained when adding R_1 and R_2:

$$R = R_1 + R_2 \tag{336}$$

Compensation for the error due to difference between the loading areas of the penetrometer plate used in soil value measurements, and of the track, was subject to Guskov's concern – concern that led to his expression of a need for universal soil values which would be independent for practical purposes from the size of the loading area.

To satisfy such a need at this time, the Russian investigators would have to accept the American soil value system, since there is no other solution. Observing their rich activities aimed at the preservation of the contributions by numerous Russian researchers, one can see such acceptance barely possible. This also may be clearly seen in their refusal to even accept Coulomb's equation without extensive mathematical alteration, as shown in the study of soil-track thrust.

To evaluate soil thrust H, Guskov (1966) adopted Katsygin soil values (equation 29), starting with well established equation (307). Thus he induced the previously reported formula (309). This formula was altered, however, utilizing vehicle weight $W = 2pb\ell$ rather than $p = W/2b\ell$. In addition he again added grouser action

$$H_{gr} = 4\,\tau_{AV} h\ell/s_t \tag{337}$$

(compare equation 266). Thus the final form for soil thrust of a track was

$$H = \frac{2\mu_m k_\tau W}{i_o \ell}\left[\ln\cosh\frac{i_o \ell}{k_\tau} - \mu_{KA}\left(1/\cosh\frac{i_o \ell}{k_\tau} - 1\right)\right] + 4\tau_{AV} h\ell/s_t \tag{338}$$

Equation (338) was the subject of speculations concerning the relationship between track and soil parameters. Conclusions reached were the same as those reached in references (Bekker, 1956, 1960) in which bevameter soil values were used. This again shows how close the Russian and American works are, not only from the method but also from the content viewpoint.

The influence of the Minsk school as well as of the American school was spreading widely. Sitkei (1967) in Hungary and Soltynski (1966) in Poland, for example, reported

in detail in their books, the state of the art prevailing in the U. S. S. R. and the U. S. A. While Sitkei's work was more tutorial than an original contribution, Soltynski and his colleague Wislicki (1969) accepted bevameter soil values in fostering their original contributions. Mihatoiu (1970), in Roumania, used Coulombian forces and Minsk methodology for evaluation of traction by particular track links.

Theoretical interpretation of experimental data naturally necessitated clarification of a number of concepts. These, however, did not necessarily follow the Minsk school. Thus Ginsburg (1968) wrote on the need for better definition of the coefficient of adhesion μ_a between the soil and the vehicle. He quoted all the Nestors of the Russian automotive practice and theory, pointing out that their definitions are either ambiguous or incomplete. The discussion that evolved was influenced by reference (Bekker, 1956), which also was quoted, although Guskov, Matsepuro, and the others were not.

A similar apparent attitude of indifference to the Minsk school was displayed by Klochkov (1967) from SibMIS. (The acronym was not clearly defined, although "Sib" indicates that the author's organization was located in Siberia.)

Klochkov referred to Krizhivitskii (1950), Rukavishnikov (1957), and Filatov (1961), all of whom were studying tracks in snow, and then proceeded with the sketchy description of his theory of track-motion resistance. He did not mention Guskov et al., as if the road from Siberia to Bielorussia were impassable. Instead he apparently tried to develop something better than was available in Minsk.

First he assumed that snow compaction causes motion resistance, and then he introduced snow-values, as shown in equation (58), which was reproduced below:

$$R = 2b \int_0^z p_{OV}\, e^{k_v \epsilon}\, dz \tag{339}$$

In this equation, p_{OV} is the bearing capacity of snow under penetration at speed v; k_v is the coefficient of snow penetration at the same speed; and ϵ is relative snow deformation defined by the depth of sinkage of the penetrometer plate z, to snow cover depth h: z/h.

The rather unclear ramifications of equation (339) became more clouded with further laconic assumptions and staggering denotations. Since there was no way of interpreting them fully, the development of R-equation is referred to below in as accurate a translation as possible.

Speed of snow deformation caused by the "approach" portion of the track may be assumed as:

$$v_a = v_o \cos(\psi/2 + \alpha/2) = v_T \sin^2(\psi/2 + \alpha/2) \tag{340}$$

where v_o is the absolute speed of the considered track portion, and v_T is the theoretical speed (compare Figure 50). α is the angle of approach and ψ is the angle of tilt of the longitudinal axis of the vehicle (vehicle trim).

Considering that the time during which the road wheel acts upon the track shoe is small, and assuming that the speed of sinkage of the shoe into the snow is uniform, the velocity of sinkage v_n of the n-th shoe was expressed by equation:

$$v_n = \frac{z_n - z_{n-1}}{s_t} \tag{341}$$

Upon introducing the speeds of snow deformation under the "approach" track portion, and under the road wheels, equation (339) took the following form:

$$R = 2b\left[\int_0^{z_1} p_{ova}\, e^{k_{va}\epsilon}\, dz + \int_0^{z_2} p_{ov2}\, e^{k_{v2}\epsilon_2} dz + \ldots \int_{z_{n-1}}^{z_n} p_{ovn}\, e^{k_{vn}\epsilon_n}\, dz\right] \tag{342}$$

Denotation p_{ova} refers to the bearing capacity at speed v of the first "approach" shoe, defined by equation (340); p_{ov2}, $p_{ov3} \cdots p_{ovn}$ refer to bearing capacities of shoes under the second, third, and other consecutive road wheels, according to the interpretation by the present writer. In equation (342);

$$\epsilon_n = \frac{z_n - z_{n-1}}{h - h_{n-1}} \tag{343}$$

Equation (342) was tested by means of the tractor T-74. During the tests the rpm, drawbar pull, and moments on the sprockets, as well as the pressure on road wheels, depth of sinkage, etc. were measured. Snow cover was 15 to 45 cm deep. Modulus of snow deformation k =0. 2 to 0. 32 gr/cm^3. Temperature was -5^{o}C to -50^{o}C.

Table 27 gives some of the results. It was reproduced as an aid for further interpretation of equation (342).

Table 27

Gear	Speed (km/h)		Sinkage (cm)	Motion Res.		Snow Deformation Resistance (by the track) (kg)	
	v_T	v_a	z	Snow Road (kg)	Snow Field (kg)	Actual	Calcul.
I	4.5	4.2	19.2	725	1450	725	667
II	5.5	5.3	19.4	790	1530	740	682
III	6.7	6.4	18.6	820	1540	720	697
IV	7.9	7.8	18.7	910	1710	800	723
V	9.9	9.6	18.5	1000	1765	865	743
VI	11.9	11.6	18.1	1160	2030	870	786

Snow cover 35 cm deep. Show bearing cap. $k_v = 0.06$ kg/cm^2

The lack of description of snow measurements, design parameters of the tractor, and other details does not enable one to check closer the work by Klochkov. Its significance, however, cannot be overlooked: although, apparently written in a competitive effort with other students of mobility problems, Klochkov's work displays the same practical form as that shown in equation (339). The introduction of "ad hoc" defined "dynamic" snow values lies in the same category. At stake only, is the question of whether various complex assumptions pay off in terms of better performance computations.

Unwittingly, perhaps, Klochkov elucidated the answer himself. His test (and hopefully his calculations) with tractor T-74 showed that the coefficient of motion resistance, f, increases under test conditions at the rate of about 1% of speed increase (km/h). One thus may ask to what extent the complexity of snow cover measurements, the uncertainty of tractor geometry and performance, variation of k_v, nonuniformity of v_T, etc. justify the "dynamic" vehicle evaluation instead of the cheaper regular "static" assessment that was previously described.

Some justification may exist if the speeds are high. But how high are they? In recreational vehicles nobody worries about power consumption as long as he has fun.

In commercial vehicles such as the T-74 tractor, used for logging or similar operations, speeds are low. It is thus obvious that a definite strategy of research was needed, which Klochkov apparently did not follow. For "dynamic" resistance to motion still appears to have low priority in the gamut of other still undefined properties and characteristics of ground mobility. In this sense Klochkov's work appears to be forgotten, like Opeiko's. But the work by the Minsk school, based on definite strategy, was going strong. It was the first work that was publicized abroad by the Russians themselves. Apparently they felt that around 1967 they had the equivalent of American work. Undoubtedly they did. And now, they seem to have even more.

The theory of the track as reported here was published in English by Katsygin and Guskov (1968) and by Guskov (1968, 1968a) in the Journal of the International Society for Terrain-Vehicle Systems. Parfenov (1968) of the prestigious NATI-NAMI further dwelt in a Russian magazine on systematization of thrust and drawbar pull definition, quoting Janosi and Hanamoto (1961) of Land Locomotion Laboratory in Detroit. Guskov (1968b) again elaborated on his track theory. And Yankin (1968) of the GOSNITI, who investigated motion resistance of a tracked tractor over snow cover, referred to more acceptable equations than Klochkov (1967). His approach may be briefly summarized as follows.

Theoretical studies showed, as he put it, that snow motion resistance of a 3-ton tractor (T-74) class may be definedby equation:

$$R = R_m + \xi' \, DP + \frac{2bhz}{z_y} \, p_y \left[e^{k_y z_y / h} - 1 \right] k_\delta \qquad (344)$$

It is not difficult to see that the soil values in this equation, p_y, k_y, are the same as those used by Klochkov (1967), although Yankin seems to have done away with the confusing denotations reflecting the speed of deformation, as discussed in conjunction with equation (339).

In equation (344), R_m is the internal, mechanical rolling resistance of the track; ξ' is an empirical coefficient (apparently taking care of load displacement), which for a 3-ton tractor is: $\xi' = 0.0565$; h is, as previously, snow-cover depth; z is tractor sinkage; and z_y is sinkage under assumption "that snow is not being displaced from underneath the track." Apparently, this means "when the path of the

road wheels is clear." p_y is bearing capacity of snow corresponding to p_{ov} of equation (339); k_y corresponds to k_v of the same equation; and k_δ is coefficient of motion resistance due to snow filling the path of the road wheels. For a 3-ton tractor, $k_\delta = 1.09$ to 1.15.

To calculate R from equation (344), show values must be determined first. To this end Yankin measured with a flat-plate penetrometer the snow curve p(z),* tractor sinkage z, and amount of snow filling the track path of the road wheels.

Tests performed with various types of snow showed that flat-plate penetrometer readings may be expressed by equation:

$$p = p_{ov}\, e^{k_v k_y / h} \tag{345}$$

where p_{ov} as before is snow-bearing capacity, though without any specifics regarding penetration speed, v; k_v is a coefficient of snow compressibility; and k_y is the coefficient that reflects the effect of snow displacement from underneath the penetrometer plate. Again, snow deformation velocities were not mentioned.

Equation (345) gives good results, according to Yankin, when snow depth-to-penetrometer plate width ratio is no more than 1.5 to 2.0. All this was considered for a three-ton class tractor. Tests performed in the field with such a tractor (DT-75) reportedly confirmed the validity of equation (344). Note again that Klochkov's "speed effect" was not considered.

But some authors thought this was not advisable. Hence, Stolbov and Kopelevich (1969) again investigated speed effect upon tractor efficiency. Their work, however, was empirical and disclosed for a T-4 tractor almost the same small magnitude of the speed effect as that reported by Klochkov (1967).

Hence, even Guskov in cooperation with Melnikov (1969) tackled the same problem. Using the previously reported formula for H (equation (308)), augmented by "grouser effect" (Equation (337)), they assumed that soil values depend on speed of soil

* This is a typical two-layer, weak-strong "soil" penetration curve (see Bekker, 1969).

deformation, in accordance with equations (9). Further analysis of motion resistance R (equation (336)) and the use of computerized analysis showed, however, that speed effect was relatively small. The result was illustrated by Figure 55.

The strength with which Russian engineers have been developing the art of off-road locomotion lies in the number of textbooks they published in recent years. That number goes beyond what we have in this country and abroad, and seems to be increasing. The most recent example is the book by Vasilev et al., (1969) on the effect of design parameters of a tracked tractor upon its performance.

The book was written for those who perform parametric analyses. It repudiates the claim that track performance is as good as it can be, and that little may be done; it offers the prospect of doing the same work at smaller vehicle weight and optimum speed, thus saving raw materials and boosting economy. The approach to the problem was based on works by

> "many research organizations in the Soviet Union and abroad, for instance, on the research performed at TsNIMESH, NATI, NAMI, and VIMe and the others. Among the foreign works, most interest was attracted by works of M. G. Bekker..." (Some of the parametric studies utilized) equations by G. I. Pokrovskii published as early as 1937, and by Janosi and Hanamoto*... and V. V. Katsygin... Experimental research provided practical recommendations for the constructor. In addition, it enabled the authors to pursue the elaboration of analytical solutions...

The up-to-date information about the theory of a track, and tracked vehicles produced in Russia, the United States and other countries, was well presented. Techniques referred to were often unique. The theories behind them were basically those expounded in Minsk and Detroit, in addition to new mathematical modelling of some problems which are too numerous to be described in the limited space of this report.

Katsygin and Bekker soil values were treated "a par." Korchunov's values applicable to "organic soils" also were described. The book appears to indicate again that the Minsk Institute, including NATI and NAMI, is leading the grand strategy of Russian research, which in principle flows in the same river bed, and with the same turbulent

* From Land Locomotion Laboratory in Detroit.

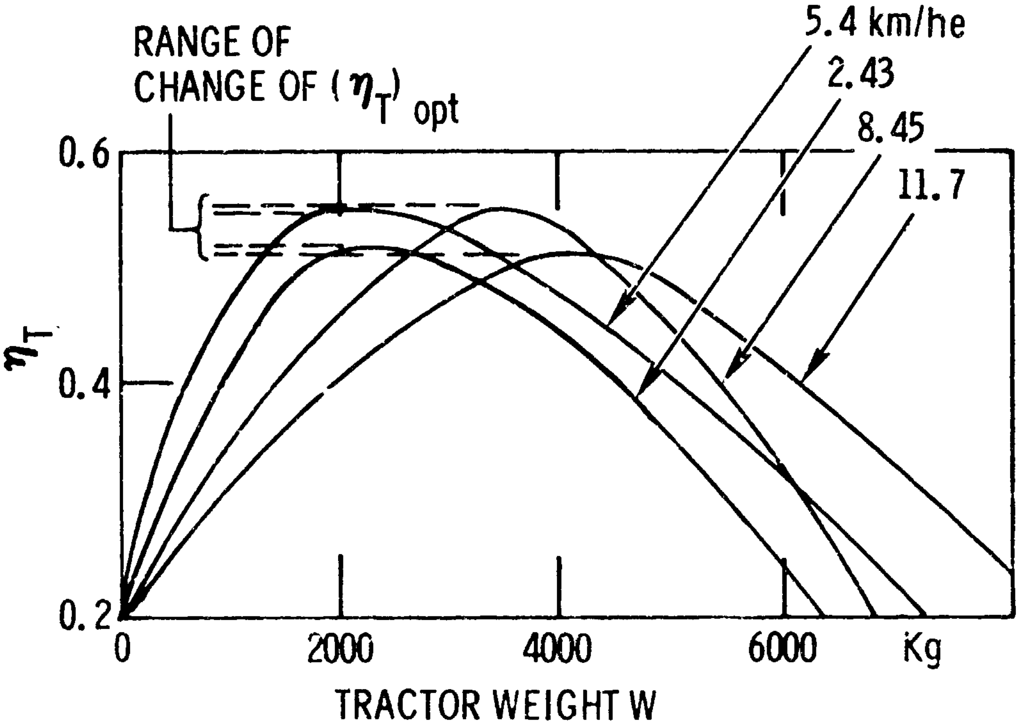


Figure 55 Effect of Tractor Speed Upon Its Coefficient of Efficiency η_T, and the Optimum Tractor Weight for $(\eta_T)_{opt}$. According To Guskov and Melnikov (1969).

current, as a small part of American research originally accomplished in Detroit. The only difference is that while the Minsk School appears to have consolidated under its banner much of Russian effort, the Detroit School was unheard of for a long time.

Dimensional Analysis

The review of literature reported here has not disclosed any effort by Russian engineers in the field of dimensional analysis. If this disinterest in the research of similitude is compared with the large amount of work performed in this area, particularly by C. J. Nuttall with the Waterways Experiment Station (for references, see Bekker, 1969), then the significance of this situation cannot be overlooked; either the Russians are guilty of gross omission, or we have overestimated the usefulness of this kind of analysis. It is suggested that the reader draw his own conclusions. The present writer made his point in reference (Bekker, 1969).

Obviously the Russian student of mobility has been very familiar with the problem. Omelyanov used dimensional analysis in 1948 in order to determine a first semi-empirical, quasi-analytical formula for pneumatic tire-soil interaction (see equation (206)).

Tsukerberg (Zukerberg) and Gordon (1965) wrote another paper that the present author reviewed with the hope of finding more about the subject matter. However, the paper does not apply to dimensional modelling of soil-vehicle systems. Instead, it is concerned with the use of small scale tire models and appropriate test equipment for the purpose of determining engineering characteristics of tire use and economy. As a sample of numerices used in this work, take the following equation:

$$f\left[\frac{PNN_p \ell}{W_i}, \quad \frac{p_i \ell^2}{W_i}, \quad \beta\right] = 0 \tag{346}$$

where P is force in the tread of the fabric: N is the number of plys; and N_p is the number of treads in one ply per 1 cm of tension area perpendicular to the road. ℓ is linear dimension; p_i is the inflation pressure; W_i is internal load; and β is the angle between the tread in the fabric, and the meridan of the carcass.

Ingenious test equipment and interesting results obtained seem to indicate that the method is applicable to tires within the discussed realm. It was apparently found to be inapplicable to the study of parametric relationships between track and wheel design on one hand, and soil properties on the other.

Surface Geometry of Terrain, and Vehicle Performance

As everywhere, the earliest descriptions of surface geometry were based on regular sinusoidal waves, and the vehicle response was analyzed with simple spring/dash pot equations of motion (Teoria Avtomobilya, published after 1948).

However, the accurate measurements of surface roughness always were important in agriculture because of soil tillage and plowing, which had to be performed at constant depth. For this purpose simple instrumentation was developed ("Voprosy...," 1960), but it had nothing to do with vehicle vibrations. Other geometrical evaluations of ground surface primarily dealt with selection of an optimum soil cut by the implement ("Voprosy...," 1964).

After the first known application of generalized harmonic analysis to off-road locomotion was published in the United States, and to highway locomotion in Germany (see references in Bekker, 1960, 1969), everyone seems to have embarked upon this type of work; Russian articles on this subject started appearing, too, very frequently.

Thus Parkhilovskii (1961) wrote a tutorial paper on spectral density of the microprofile of the road, and on vehicle vibrations. All the references were Russian, based on standard definitions and methodology which originated twenty years ago, in this country with Wiener, Blackman, Tukey, St. Denis, Pierson, Notess, Crandall, and others. Pokrovskii's work closely resembled a chapter by Crandall et al. (1958).

Since the new method required much mastery of statistical inference, and above all, the availability of computers, it developed very slow. In addition it was and still is very expensive and inaccurate, if not backed by experimental monitoring of major inputs and checking of the outputs. It was probably for this reason that Torchinskii (1962) of the Dnepropetrovski Institute for Engineering and Design (Dnepropetrovskii Inzhenernostroitelnyi Institut) devised a semi-empirical approach to one of the paramount problems of surface geometry and vehicle motion resistance.

His approach was, interestingly enough, based on a much earlier work by Birulya (1949), who proposed the following equation for the coefficient of motion resistance on a rough road:

$$f = \frac{W_r v^2}{13gWr} \rho_1 \frac{\Sigma h}{\ell} \qquad (347)$$

Here W_r was weight of unsprung mass; v was vehicle speed; r was rolling radius; and ρ_1 was the coefficient of road roughness, which expressed the portion of energy loss that is not recoverable as a result of rolling down the slope of the rough spot of the road. It also reflected other factors involved in the inaccuracy of measurement of roughness and enveloping power of the tire. $\Sigma h/\ell$ was the sum of all the elevations of roughness per 1 m of the road.

Torchinskii was concerned with road measurement by means of an unspecified prolilograph, and with the effect of the instrument design upon the data thus obtained. He recommended the use of a recorder mounted on the investigated car, rather than on a separate chassis. The car would record spring deflections, and upon processing give the $\Sigma h/\ell$-value for the given vehicle and speed:

$$\Sigma h/\ell = \rho_2 S_m \qquad (348)$$

where ρ_2 was the transfer coefficient between the spring deflection and road roughness and S_m was the integrated reading of the "roughmeter" in cm/km. Thus Torchinskii's formula took the following shape:

$$f = f_o + \frac{W_r v^2}{13g\,Wr} \rho_1 \rho_2 S_m \qquad (349)$$

where f_o was the coefficient of rolling resistance on a smooth road. Birulya determined coefficients ρ_1 and f_o by coasting the vehicle. Torchinskii wanted full drive simulation, and introduced torque T measurements. In this approach

$$\frac{T}{W_r r} = f_o + \frac{Wr}{13gWr} \rho S_m v^2 + \tan\beta \qquad (350)$$

where ρ was the summary coefficient of roughness and β was the slope. Air resistance was omitted in equation (350) by the present writer. Rolling radius r was

$$r = \ell/2\pi n \qquad (351)$$

where ℓ was the distance traveled, and n was the corresponding number of rpm's.

This simplistic approach undoubtedly gave more accurate, faster, and cheaper results than many sophisticated computer programs so fashionable today. Of course, it has limitations because it "integrates" ground roughness $\Sigma h/\ell$ only for the given vehicle. It should not be difficult, however, to improve the method by introducing modern profilometers and corrections for enveloping power of the tires (compare Bekker, 1969).

Torchinskii and Birulya's treatment of the problem was perhaps the only original one. The others faithfully followed the regular mechanics of transient states of the vehicle, and computerized the procedures by using methods of statistical approach, though not to the same extent as in the United States.

But Komarov and Zatserkovnyi (1962) of Lvov Institute of Technology published a rather conservative theory of vehicle vibrations which was seemingly based on Lehr's (1934) classic. Their treatise dealt with variable suspension constants.

However, as the need for computerized approaches was emerging with great force, Rotenberg (1963) published in the organ of a Committee for Mashin Design and Automation, a tutorial paper on computer application to automotive design. The discussed programs encompassed not only the suspension and vehicle geometry design but also vehicle dynamics as a function of transmission type. The author dwelt on rather simplified schemes including driver-vehicle models, and did not elaborate the details. He listed problems of vehicle modelling and exemplified them with simple data (Figure 56).

Parkhilovskii and Zaitseva (1964) went deeper into the methodology of "stationary ergotic process" of vehicle vibrations and computerization of the calculations. Their work was sponsored by Gorki Agricultural Institute and Automobile Works (Gorkovskii Selskokhozyaistvennyi Instytut and Gorkovskii Avtozavod); they used the MN-8 computer. Equations of motion with four degrees of freedom for a linear system were developed for that purpose. A statistically defined, random road profile was used as input. Acceleration, displacement, pitch, etc., of the vehicle were

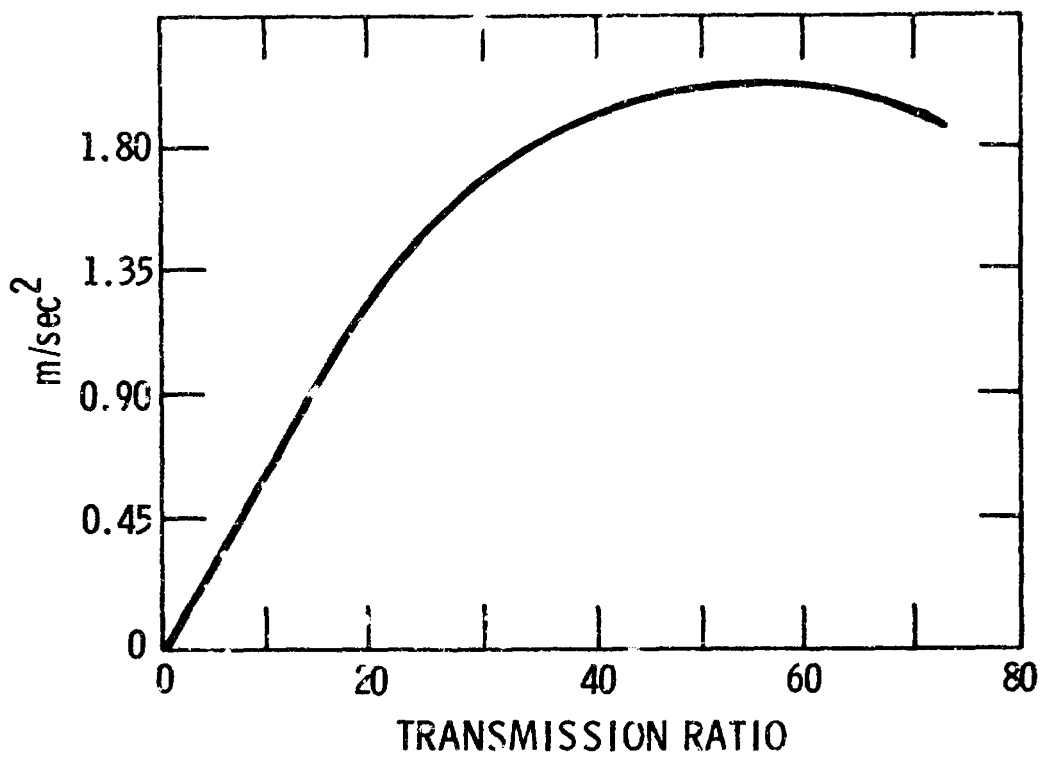


Figure 56 Maximum vehicle acceleration versus transmission ratio (Rotenberg, 1963)

considered in the output. This excellent paper was illustrated with an example calculated for an assumed vehicle that was fully described in terms of geometrical and mass-force characteristics required in that type of calculations.

The changes of correlation function, and its dependence on various input parameters, were described. Again, only Russian authors were quoted. It appears that the work was parallel to that by Mitchke (1962) in Germany. American work on power spectral density analysis for runways, roads, and terrain (for references see Bekker, 1969) undoubtedly had much influence upon Russian research. Pevzner and Tikhonov (1964) gave a detailed account of spectral densities of roads and attempted to generalize road roughness into categories defined by empirical equations. Again, only Russian literature was quoted.

A conventional though much refined technique was used to define stability of dump trucks on side slopes when the dirt was unloaded (Zaks, 1964). The same technique was used for semi-trailers (Vzyatyshev, 1964).

However, Rotenberg (1965) continued the development of generalized techniques for performance evaluation, by means of computers (EVM). These included descriptive listing of procedures for calculation of speed on slopes, fuel consumption per hour at varying gear ratios, pitch and bounce, frequency and damping, etc. This was another tutorial, popular presentation, apparently selling the computer even for more complex evaluations such as man's role in the system and ride comfort. (For details of all the reported references, see Bekker, 1969). This time an American author named W. R. Morland was referred to.

There is no doubt that the early sixties witnessed an increasing effort in selling the computer to automotive engineers. Relatively popular or unavoidably abbreviated and simplified exposition of the problems indicated how much education was needed by the Russians in statistical analysis – a parallel to their American colleagues of automotive industry, who were at the same time exposed to a similar treatment (see Bekker, 1961; Mitschke, 1962; Bekker and Butterworth, 1965; for more references, see Bekker, 1969).

However, the quality and professionality of exposition, and the audacity of tackling more complex problems, were steadily increasing, apparently with the rising understanding of the problem by the readers of Avtomobilnaya Promyshlennost (Automotive Industry). Hence Atoyan and Akopyan (1966) of Lvov Institute of Technology and Lvov Automobile Works presented an extensive statistical analysis based on power spectrum analysis in order to show the load regimes of automobile suspension. The method was professionally developed and load factors were determined in terms of rms. These led to the definition of the corresponding stresses. Only Russian literature covering the period of 1961-1964 was quoted.

More tutorial material, related to ride comfort, was provided by Parkhilovskii (1966), though again in a popular descriptive manner.

Tchaikovskii (1967) further championed the cause of computerization of automotive research. But in his study of stabilization of steering wheels he developed deterministic equations of motion and a computer flow chart for the purpose of defining steering stability criteria of the vehicle. In spite of the abundance of work in this field, in practically every country only Russian references were quoted, indicating rapid progress in the discussed area.

On this background, it was surprising indeed to find the textbook on wheeled cross-country vehicles by Grinchenko et al., (1967) which did not mention the development of new methods. The book reproduced fine design details of Russian and foreign vehicles as well as elements of design and engineering, but dwelt only on simple, antiquated equations of equilibrium of suspension loads and vehicle load distributions.

Apparently Russian automotive engineers had not digested at that time the modern statistical methods of defining transient states, or did not need them in order to design successful vehicles – or both. This was not puzzling, however, when it is realized that similar reaction was displayed in the United States and elsewhere, with a notable exception of West Germany.

However, progress did not stop. The slowness of the spreading of statistical methods was undoubtedly due to the scarcity of computers. For these were assigned with first priority to atomic and space research, management, and production control (Berenyi, 1970).

Thus, practical or tutorial rather than research papers on statistical approach seem to have prevailed. Medvedkov and Yar'kov (1968), for example, outlined a computer method for evaluation of vehicle speed, assuming regular equation of motion on a smooth road, without vibrations. Belen'kii and a group (1968) of PhD's from Minsk Institute of Technology, Minsk Automobile Works and Institute for Machine Design, wrote another study on vehicle's energy loss due to vibrations. This time the paper was not based on a semi-empirical equation, but on a series of equations of motion covering pitch and bounce of a vehicle with an arbitrary number of axles. The general form of the equations was as follows:

$$\left.\begin{aligned} &\ddot{x} + \sum_{i=1}^{n} \beta_i (F_{i1} + F_{i2} + F_{i3}) = 0 \\ &\ddot{\varphi} + \sum_{i=1}^{n} \lambda_i (F_{i1} + F_{i2} + F_{i3}) = 0 \\ &\ddot{Y}_i - \gamma_1 (F_{i1} + F_{i2} + F_{i3}) + F_{i4} + F_{i5} = 0 \end{aligned}\right\} \qquad (352)$$

where i = 1, 2, 3...n is the consecutive number of the axle; β_i is the portion of sprung mass acting on i-th axle, affecting pitch; λ_i is the coefficient of coupling with i-th axle; γ_i is the ratio of sprung to unsprung masses; x and y are coordinates of the system; and φ is the angle of pitch. F_1, F_2, F_3, F_4, and F_5 are forces in the spring/dash pot scheme of the suspension and the tire.

Equations (352) were solved for a number of vehicles by using computer "Minsk-2," and the effect of various design parameters on energy loss of the system was analyzed. Attention was given to the magnitude of losses in shock absorbers, "dry friction," tire deformation, etc. Calculations were performed under the assumption of travelling over dimensionally regular and evenly spaced humps.

Armashov and Zheglov (1968) addressed themselves to the problem of vibrations of one-axle trailers. Both authors were studying at the Moscow High Technical School, named after Baumam (MVTU). The problem they tackled was deterministic. But their interesting solutions may have been applicable to the evaluation of the configuration of the Gama-Goat, and to improvement of its ride characteristics.

Engineers from the Institute for Construction of Roadbuilding Machines (VNI Stroidormash), Gaitsgori, Malinovskii and Pasynkov (1969), dwelt on tutorial formulation of vehicle vibrations in man-machine system. Iofinov and Taipov (1969) of Bashkirskii Institute for Agriculture wrote on mathematical modelling of tractor-implement systems, and on the use of computers for that purpose.

All these efforts were steadily growing in strength and aimed in one direction: analysis of complex terrain-vehicle systems. For the computerization of mathematical modelling and the introduction of statistical inference are inseparable necessities with system analysis, and discardable luxuries without such analysis.

CHAPTER VI
TOWARD TERRAIN-VEHICLE SYSTEM OPTIMIZATION

Introduction

Generating the analysis of Russian literature reported in the previous chapters could not fail to impress this reviewer with a continuing, evolutionary development of mathematical modelling of soil-machine relationship.

The evolution of this development was as much subject to Darwinian indeterminancy as it was an effect of the rational school of thought founded on an incessant search for better models and input data, all based on applied mechanics and automotive engineering.

This sharply contrasts with the work performed in this country, where empirics totally alien to the mathematical modelling of terrain-vehicle interaction and automotive practice has been pursued for decades, with little concern for the earlier, more rational attempts that were parallel to those in Russia, Germany, and England.

Even the present situation appears paradoxical inasmuch as the "consolidated" American activity is primarily pushing the development of vast, all encompassing do-it-all computerized programs, although such solutions, if possible at all, require a decade of prior development of mathematical models, data banks, and inputs that define boundary conditions of specific practical problems instead of vast theoretical schemes.

In this context, it is noteworthy to stress again that while we are still being confronted with such arbitrary measures as "G" value or "rated cone index" and various "mobility indices," the Russians gave their values of locomotion a definite physical meaning of a mathematical formula, gradually encompassing the terrain-vehicle system. Attempts of solutions such as those by Tsymbal (1958), Rokas (1965), and Poliakov and Nafikov (1969 a) have not been found in textbooks on soil-vehicle relationship, for their arbitrary indices were originally conceived for empirical correlation of soil-working machinery parameters, with the draft of ploughs and tillage equipment, with scraping and bull-dozing, or with plant physiology. And even such indices as "DORNII" have found only limited application in an evaluation of soil cutting by bulldozers or scrapers (Zelenin, 1950, 1968, 1969; Fidaev, 1970).

In general, this situation is full of contrasts: the Russian mathematical models and data banks appear to be waiting for an allotment of more of their scarce computer time, while our over-expanded computer systems wait for more and better mathematical models and inputs.

If this evaluation of Russian R&D in off-road locomotion is correct, then two conclusions are inevitable:

- Meaningful terrain-vehicle system analysis in Russia is near to implementation because they have worked long enough on mathematical models and databanks. They also have a large number of highly qualified workers. The computers may do the job rapidly, as soon as they are made available in sufficient numbers.
- Our terrain-vehicle analysis references may be far off, because we need a number of years (depending on personnel availability) to develop the databanks and better mathematical models for the idling computers.

In the following lines, an attempt will be made to chronologically describe and to analyze the Russian work for the purpose of further verifying and expanding the conclusions.

Early Parametric Analyses

System analysis as such is not new. It has been performed since the beginning of engineering activities unnamed, or under a different name, whenever an optimum of form-size-weight-energy balance of a machine or its element were sought.

In this sense the work by Morin (1840-41), Bernstein (1913), Letoshnev (1936), Goriachkin (1937), Giuzdev (1944), Chudakov (1962), Katsygin (1964), Guskov (1966), Vasiliev et al. (1969), Gorin (1970), Kienin et al. (1970), and many others whose accomplishments will be reviewed in this chapter, have always performed a parametric analysis or developed a method for such analysis concerned with the optimization of factors involved.

As mentioned before, the Russian system analysis could not have progressed beyond limited evaluations because of the lack of generalized soil values independent of

vehicle size. The attempts to correct that deficiency date back to Puzyakov (1931) and the others, as reported in a paper by Saakyan (1954).

The solution offered by Saakyan was shown in equation (24) and was used, among others, very recently by Guskov and Melnikov (1968), and Guskov (1966, 1968). Apparently this was accepted as a stop-gap, though it was not considered entirely satisfactory.

Interestingly enough, in 1960 the Minsk "Voprosy" published an article (Vol. III) about wheels, using in their parametric analysis of wheel draft, the old Bernstein-Letoshnev equation (12) and Goryachkin-Housel equation (18), both of which as reported in Chapter II, attempt to minimize the effect of wheel width upon the measured soil values k, A_o and B_o. All this indicated a trend toward the generalization of mathematical models, and hence toward the modelling of larger and larger systems. The "Voprosy..." were concerned among others with the following interactions of various design parameters of a tracked vehicle and the soil:

- slip versus pull
- motion resistance versus maximum drawbar pull
- motion resistance – soil shear versus maximum drawbar pull
- motion resistance versus sinkage.

An example of a semi-empirical parametric evaluation of motion resistance f, coefficient of adhesion μ_a, and drawbar pull DP as a function of ground pressure p was shown for a tractor of C-80 type in Figure 57. Another example was displayed in Figure 58 which shows the change of f as a function of the location of tractor's CG.

The objective of that work was to predict coefficients of efficiency and effectiveness of a tractor-soil working machine system. To this end, coefficients of efficiency of particular machines η had to be defined first. Extensive literature and databanks on this subject were published in "Voprosy..." (1960, Vol. V). Alignment charts for η, expressed in terms of soil and machine parameters such as k, μ_o, etc., were produced together with numerical examples, and undoubtedly represent fine introductory material for computerization which had to wait for about a decade before computers became available at all. Optimization of tractor performance on a statistical basis also was reported in the same volume (Figure 59).

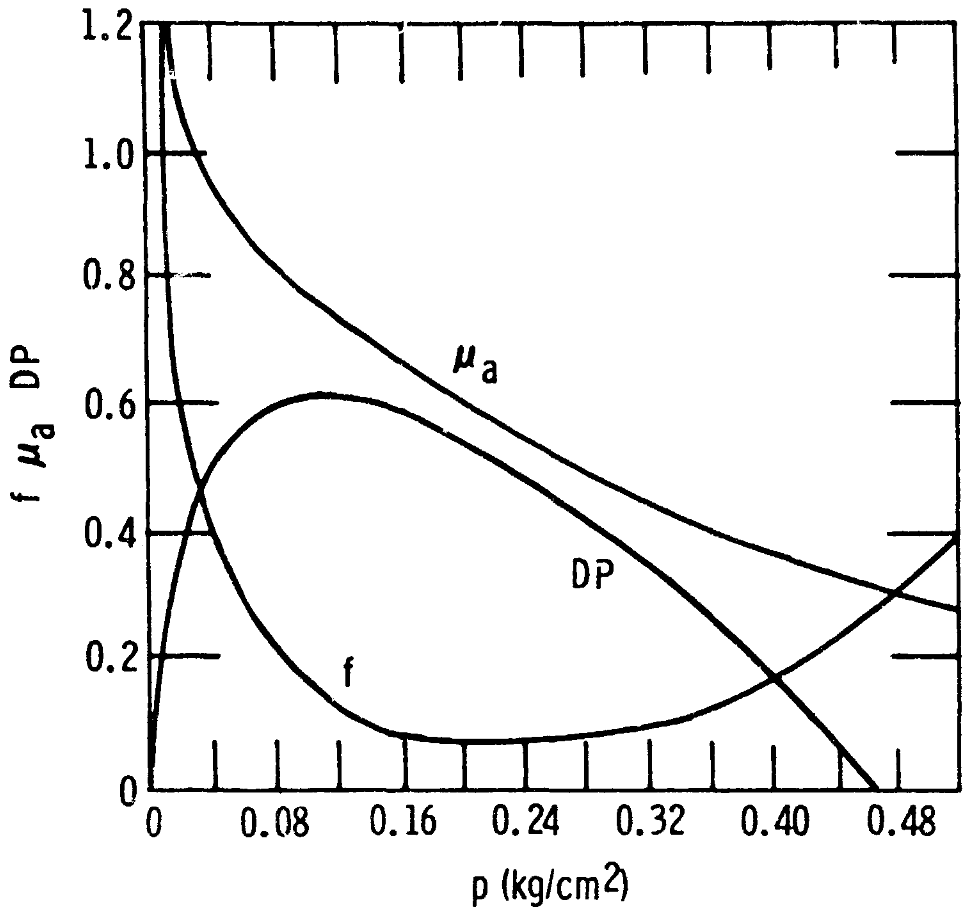


Figure 57 Parametric comparison of f μ_a DP and p from a semi-empirical evaluation of a tracked tractor (Voprosy... 1960, Vol. III)

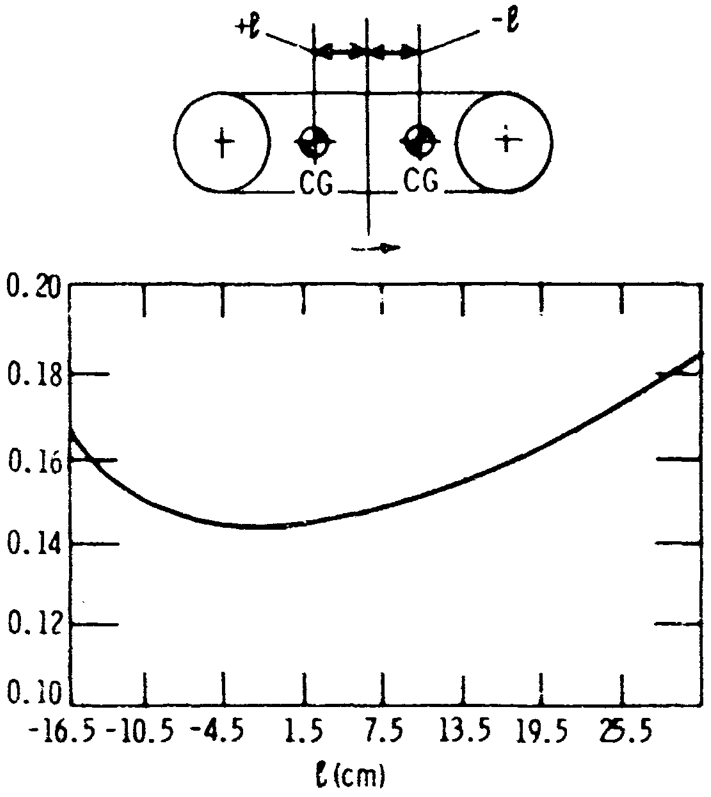


Figure 58 Change in motion resistance f as a function of location of tractor's CG ("Voprosy... " 1960, Vol. III)

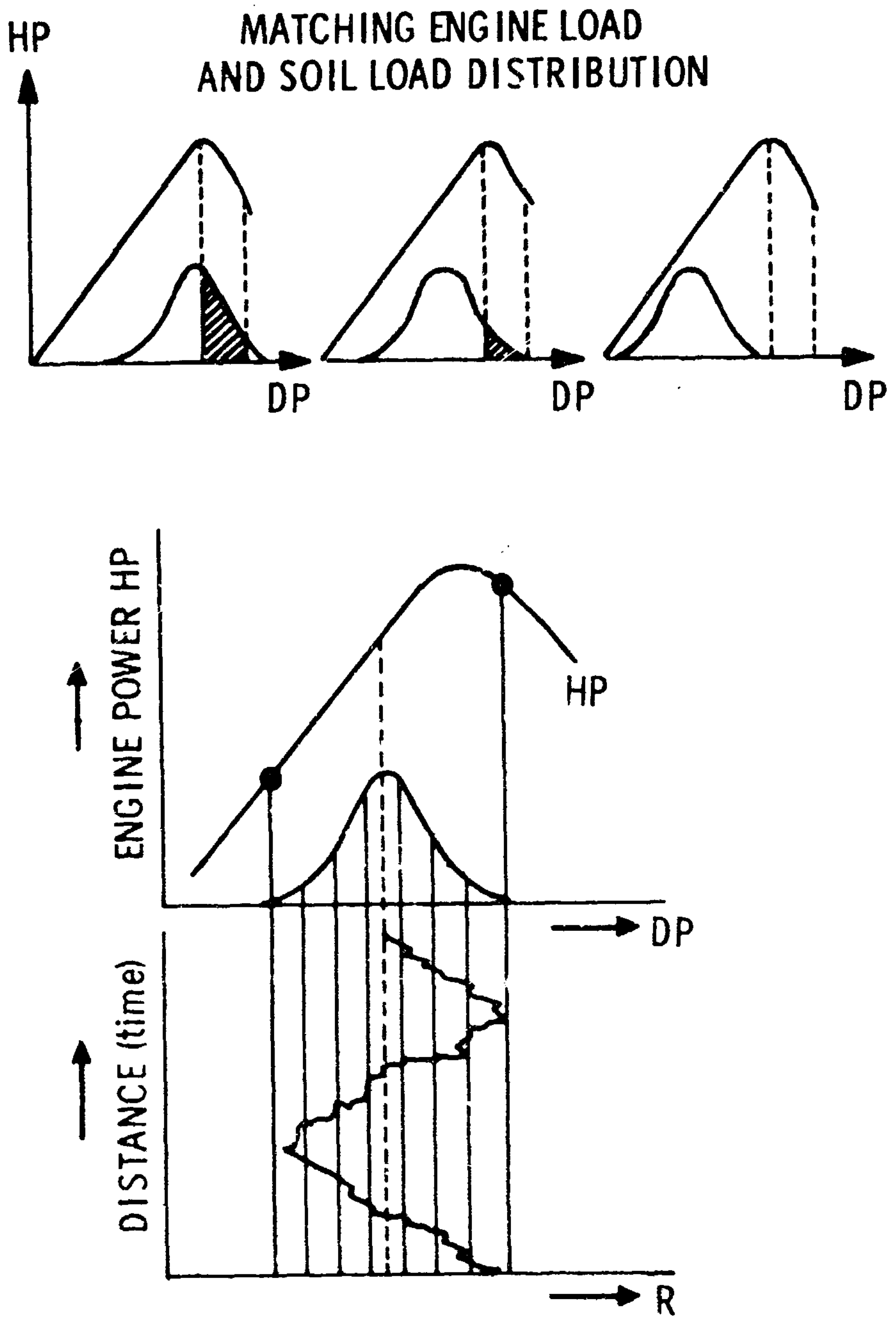


Figure 59 Statistics of motion resistance distribution (R) and the utilized engine power (HP) as a function of the related drawbar pull (DP). From "Voprosy..." 1960, Vol. V.

The tabulation of all kinds of input represents a fine databank, in spite of the lack of a generalized soil-value system. Naturally, the general trend was directed to finding ways and means of improving the effectiveness of various aggregates of equipment, which was analyzed in another chapter. The abundance of information was such that it was impossible in this short review, to reproduce or even to refer to numerous alignment charts which enable one to quickly evaluate coefficients of efficiency of a large array of tractor-machine systems.

Whatever was the accuracy of these evaluations and optimizations, it was overshadowed by the mere existence of the method, which if continuingly developed would satisfy the most modern requirements of system evaluation. To illustrate the character of this method a nomogram for selection of parameters of tractor-machine aggregates was reproduced, in an unchanged form, in Figure 60. Here, γ means the ratio of tractor weight to the draught of the implement (trailer); ηs are coefficients of efficiency of drawbar pull (slip) and tractor transmission; and f is motion resistance. It is hoped that this incomplete description of Figure 60 gives the reader an idea of parameters involved, and the picture of a practical approach to their optimization.

Many other examples of parametric evaluations could be further quoted. The authors of the "Voprosy..." (1961, Vol. VII) consistently adhered to the mathematical modelling and underscored the need for more scientific, rigorous work, always validated by experiment:

> "contemporary experimental studies on soil-working mechanics depend to a large extent on scientific-engineering foundation. When formulating tasks of a broader scientific nature, it is necessary, however, to simultaneously widen the basis for laboratory-engineering work."

The philosophy annunciated three years later in this country though not official was widely practiced on the assumption that:

> "It must be conceded that most major steps forward come about either as a result of sudden insight or inspiration... or as a result of patient, painstaking sifting of carefully collected facts and measurements... If (such programs are) carefully performed and well documented, and if they contain enough measurements... (they) have one saving grace: there is always the possibility that the data may provide the source from which a vehicle mobility (Kepler or Newton) will find inspiration and insight," (Knight and Freitag, 1964).

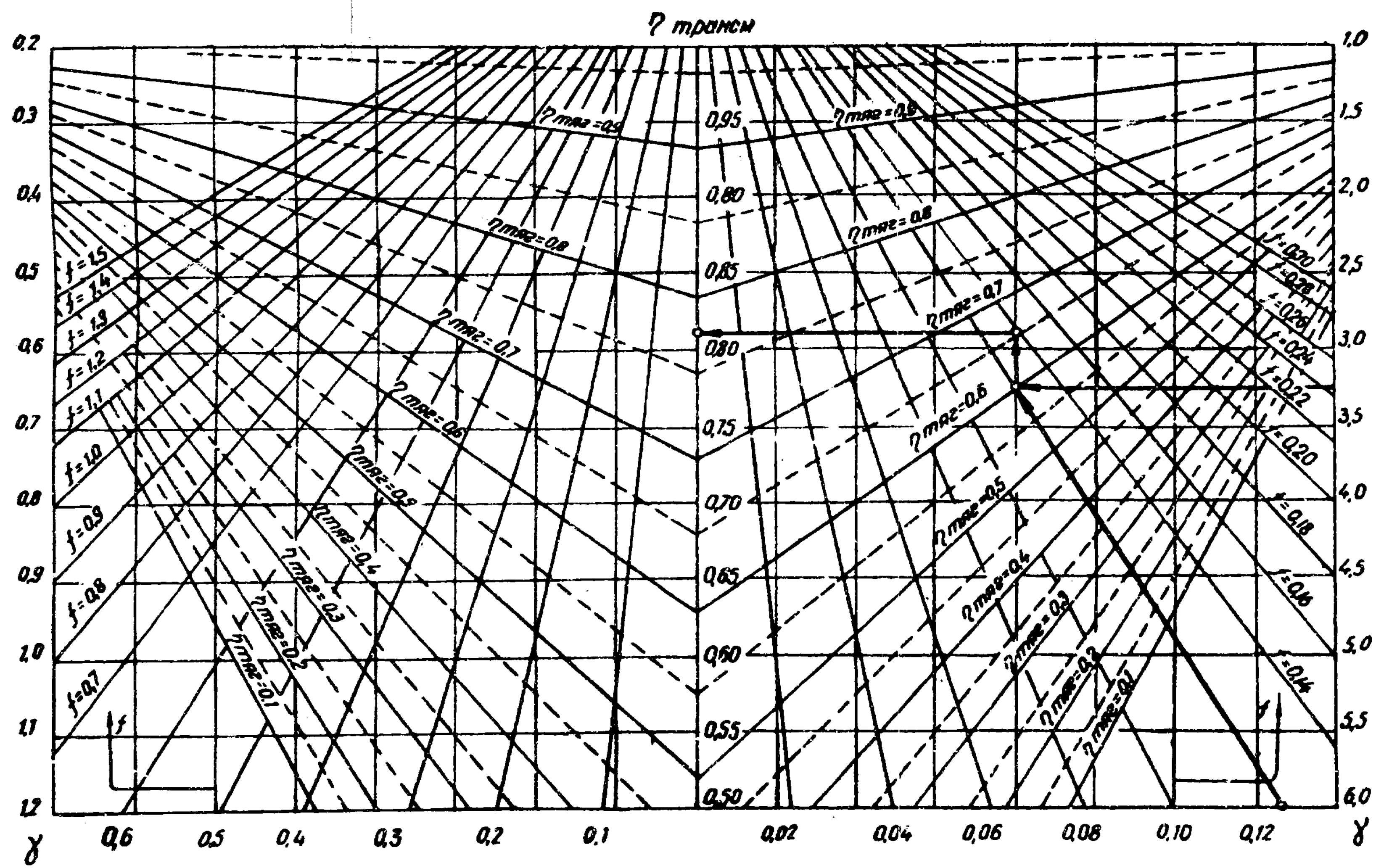


Рис. 3. Номограмма для выбора параметров тракторных агрегатов.

Figure 60 Alignment chart for determination of parameters of tractor-machine aggregates ("Voprosy ..." 1961, Vol. VII)

The Russian automotive and tractor engineers did not wait for the Newtons and the Keplers. They went ahead in their own way, and made significant progress. In the meantime, we collected tons of data and computer tapes, which wait for someone who could make sense out of them.

Mathematical Vehicle Modelling

Implementations of parametric and systems analysis requires prior definition of mathematical models and value standards. The early nineteen sixties appear to be very prolific in providing such models and standards. A series of methodological contributions appeared with particular frequency in 1961.

Lysov (1961) of NAMI wrote on the method of quantitative determination of vehicle maneuverability in turns. Pogosbekov (1961) of the Kuban Agricultural Institute defined the coefficient of efficiency of driving wheels of the vehicle. Antonov (1961) wrote about the method of a diagrammatic analysis of stability for multi-axle vehicles, and Klychkov (1961) of TsNIIME's busied himself with the determination of the optimum specific vehicle power, prior to and/or during the design stage.

In the same vein, Kuznetzov (1962) proposed his soil "durometer" described in Chapter IV, while Kurzel (1962) of NAMI worked out a method of determining fuel consumption and speed of a vehicle with hydro-dynamic transmission for variable regimes of work. Antonov (1962) wrote again on the assessment of turn stability of multi-axle vehicles. Chudakov's (1962) textbook on tractor and automobile theory, used in the Russian schools, dwelt on the evaluation of engineering and economic design trends, with the purpose of predicting the future in terms of specific parameters.

These are but a few samples of literature available to this writer, which were published primarily in the official organ of the automotive industry.

The Minsk School pursued a similar activity which undoubtedly inspired much work in the automotive field. However, their primary goal was to increase the effectiveness and decrease the cost in the operation of tractor-implement aggregates. To this end, the efficiency versus design of these aggregates was worked out again and again, very much in the same fashion and for the same purpose as those required for systems analysis (compare Bekker, 1969, and "Voprosy, 1962, Vol. VIII). The data and the method represent a nearly perfect attempt of what may be called now the "mission

definition; " and a less perfect attempt at a definition of the "environment" – less perfect, because of the lack of generalized terrain-value system.

Nevertheless, the mathematical models, the input data, and the numerical examples of evaluation of

- the optimum location of CG of a tractor,
- motion resistance as a function of length-to-width ratio of a track,
- soil thrust for various ratios, of linear dimensions of the ground contact area,
- energy balance of a tractor in uniform motion,
- drawbar pull as a function of track form,
- optimum length-to-width ratio of a track,
- effectiveness of wheel width increase,
- grouser effect, etc., etc.,

have no parallel in the quality and amount of material presented here.* in most cases, the calculations were tested with experiments.

If the textbook on design and theory of wheeled tractors for earthmoving machinery by Ul'yanov (1962) is a measure of the trend permeating the civil engineering school of thought, then it may be concluded that a similar trend characterized the R&D in this area too. This is no surprise since the bibliography quoted by Ul'yanov contains familiar names of Babkov, Birulya, Zimelev, Knoroz, Lvov, and Letoshnev, to name a few.

In a chronological review of work that aimed at what is called today "system analysis" though this term was not used in Russia until about 1970, one must further mention the Minsk School.

"Voprosy..." 1963, Vol. X, starts with the definition of factors which define effectiveness of tractor-machine aggregates. This was investigated with an apparent effort of establishing a meaningful databank with innumerable tables and records, as

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* Comparable, from methodological viewpoint, are works by the British NIAE, German Agricultural Institute in Volkenrode, and the U. S. work by the Land Locomotion Laboratory in Detroit, performed between 1954 and 1961.

well as with numerical examples illustrating the data processing for the purpose of a semi-empirical definition of effectiveness. Because it is impossible to present even an abbreviated form of the material mentioned, it is hoped that the following list of topics will give the reader an idea of the scope of this work:

- tractor effectiveness versus soil types,
- effect of ground-surface geometry and the length of the swath, upon effectiveness of agricultural machinery,
- particulars of work in fields strewn with stones,
- selection of vehicle-machine types,
- load carrying capacity and effectiveness of transporters,
- soil compaction, etc.

Birth of System Analysis

"Voprosy..." (1964, Vol. XIII) expanded these topics into the study of a

- definition of optimum parameters of mobile agricultural equipment,
- definition of a theory for selection of optimum parameters of mobile agricultural machinery.

The study authored by V. V. Katsygin was referred to by Academician M. I. Matsepuro, and dealt with very broad philosophy of system approach to the optimization of the machine-environment-mission complex. It was reiterated by Professor V. V. Guskov, and was first made available in English in 1968, during his collaboration with Dr. A. R. Reece at the University of Newcastle upon Tyne. It is this second version originally published in the "Voprosy..." (1964, Vol. XIII), which is briefly discussed here because it represents an introduction to the further work on terrain-vehicle system otpimization by the Minsk School.

Parameters which determine drawbar pull efficiency and operational economy are the weight of the tractor, its size, form, engine power, speed range, etc. Optimization of all these parameters at the design stage is based on the assumed criteria. If two tractors having design parameters A_1, B_1, ... K_1 and A_2, B_2... K_2 are to be compared, then the pertinent parameters and their groupings must be assessed against each of the criteria. In this process, performance characteristics such as, for example, efficiency η, output (productiveness) O, cost C, versatility (for instance,

adaptability to work in the Arctic and the temperate zone) T, reliability and/or life M, etc., are functions of parameters A, B, C...K:

$$\left.\begin{array}{lcl} \eta & = & f(A,\ B,\ \ldots K) \\ O & = & \Psi(A,\ B,\ \ldots K) \\ C & = & \varphi(A,\ B,\ \ldots K) \\ T & = & \beta(A,\ B,\ \ldots K) \\ M & = & \gamma(A,\ B,\ldots K) \end{array}\right\} \tag{353}$$

The individual optimum then is defined by equations:

$$\left.\begin{array}{l} \frac{\partial}{\partial A} f(A,\ B\ldots K) = 0 \\ \frac{\partial}{\partial B} f(A,\ B\ \ldots K) = 0 \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \frac{\partial}{\partial K} f(A,\ B\ \ldots K) = 0 \end{array}\right\} \tag{354}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\left.\begin{array}{l} \frac{\partial}{\partial A} \varphi(A,\ B\ \ldots K) = 0 \\ \frac{\partial}{\partial B} \varphi(A,\ B\ \ldots K) = 0 \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \frac{\partial}{\partial K} \varphi(A,\ B\ldots\ K) = 0 \text{ etc., etc.} \end{array}\right\} \tag{355}$$

Equations (354), (355), and three other similar formulas resulting from the differenciation of the remaining equations (353), define either the minimum or the maximum, depending on the criteria chosen. For instance, equation (354) will help define the maximum efficiency η, whereas equation (355) will define the minimum of cost C. The question if these equations have an optimum at all was reportedly solved with the Lagrange multiplier method.

Thus from a mathematical viewpoint the problem and its solution are well at hand. However, the selection of proper performance criteria may be very difficult, and is often subjective. For example, speed v of the tractor may be defined for a maximum

output O (Figure 61). Aiming at the optimum, v_η, may produce low output, O_1, which increases cost, C. On the other hand, if the design target is the optimum, v_O, the performance may drop to the low efficiency, η_1. A compromise criterion for optimum v lies in the range:

$$\text{opt } v_\eta < \text{opt } v < \text{opt } v_O$$

Guskov discussed three ways of selecting design criteria, supposedly following Katsygin and Matsepuro's reasoning. One way is to assume that only one criterion is to be considered. This simplifies the solution since the optimum design parameters are based on only one set of equations (354), (355)... etc. If all the N criteria are equally important, then the design optimum may be obtained by taking the mean value of the optima:

$$\left.\begin{array}{l} A_{opt} = \dfrac{(\Sigma A_{\eta\, opt} + A_{Oopt} + \ldots A_{Mopt})}{N} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ K_{opt} = \dfrac{(\Sigma K_{\eta opt} + K_{Oopt} + \ldots K_{Mopt})}{N} \end{array}\right\} \tag{356}$$

And if a specific importance is attached to each criterion it is necessary to take each into account. The difficulty then is that the probabilities P_1, P_2, $P_3 \ldots P_N$ of occurrence of each separate optimum is usually unknown:

$$\left.\begin{array}{l} A_{opt} = \dfrac{\Sigma\,(P_1 A_{\eta opt} + P\, A_{Oopt} + P_N A_{Mopt})}{\Sigma\,(P_1 + P_2 + \ldots P_N)} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ K_{opt} = \dfrac{\Sigma(P_1 K_{\eta opt} + P_2 K_{Oopt} + \ldots P_N K_{Mopt})}{\Sigma\,(P_1 + P_2 + \ldots P_N)} \end{array}\right\} \tag{357}$$

Simplified examples of the application of this general line of thought to terrain-vehicle system optimization was published by Guskov (1966, 1968, 1968 b). A more general, though abbreviated, outline of the theory of system evaluation was given by Katsygin (1964).

This was the first, as far as it could be ascertained, series of publications which outlined the general philosophy of terrain-vehicle system analysis. The need for the best

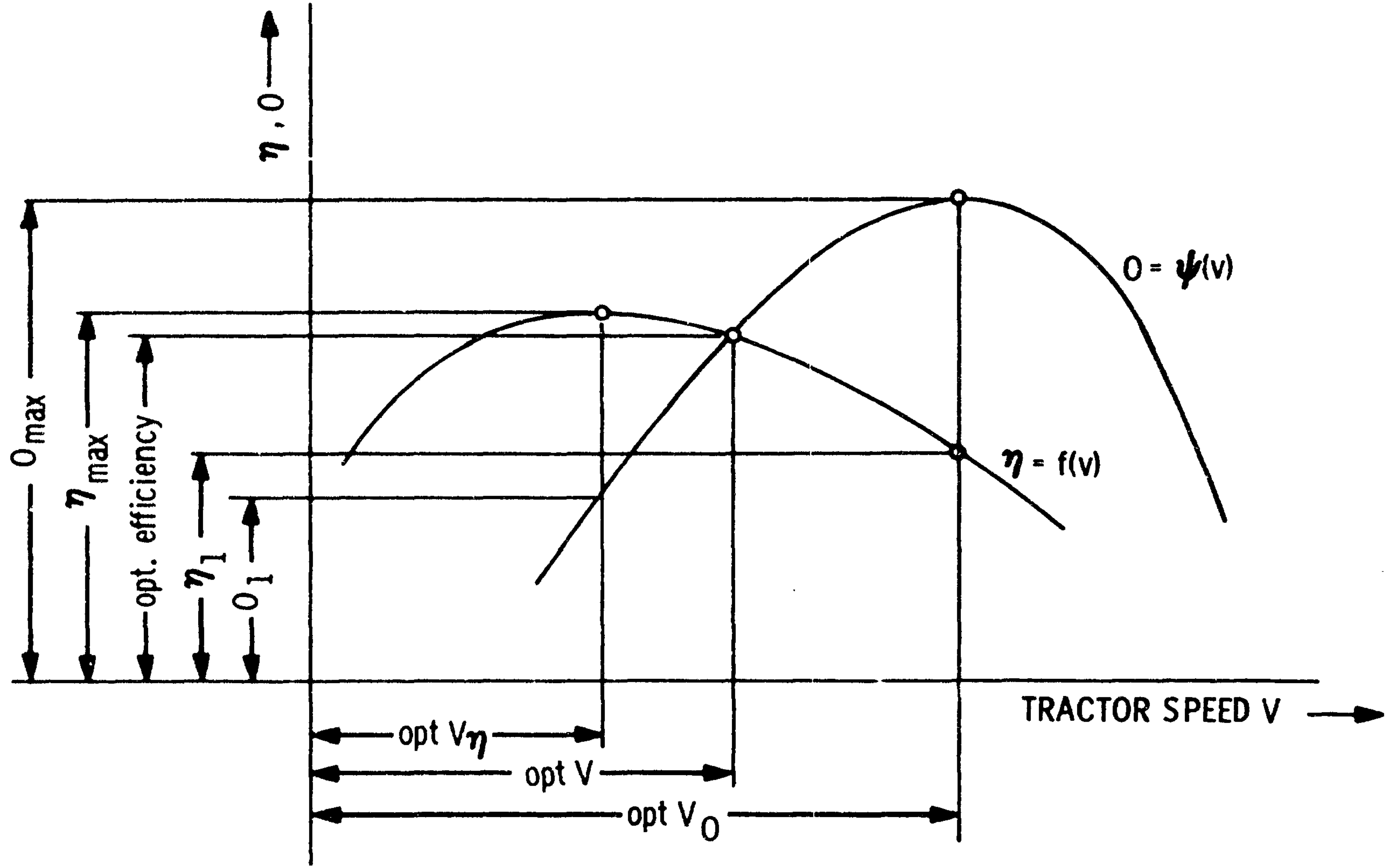

Figure 61 Optimization of Tractor Speed, Considering Output O and Efficiency (Adapted from "Voprosy..." 1964, Vol. XIII in Accordance with Modification by Guskov, 1968

possible mathematical modelling of functions (356), (357), etc. was thus implicitly postulated. Probably, for this reason the "Voprosy..." (1964, Vol. XIII), devoted many pages to soil values and their relation to vehicle design and performance parameters, as previously described in Chapters II and V. In addition, much space was devoted to mathematical modelling of such problems as:

- energy consumption in soil working by various agricultural machines
- theory of optimization of design and performance parameters
- modelling of soil draft versus speed
- optimization of speed and soil cuts
- optimization of tractor parameters, etc.

The final chapter of the "Voprosy..." (1964) was devoted to the methodology and organization of research. Scientific-engineering approach was stressed over and over again, and the team, scientist-engineer, was subject to general discussion from the organization viewpoint. Experimental verification of theories was strongly emphasized. The system approach was clearly emerging:

> "Development of agricultural mechanics makes it possible to solve problems theoretically instead of empirically... Modern level of scientific knowledge (also) enables one to perceive each phenomena in close relationship with the others...
>
> Complexity of modern technological systems, particularly those working with automatized processes and machines, and composed of a series of functional relationships, needs mathematical treatment..."

The aim of such an approach was not the invention of new gadgets but the establishing of rational design parameters of tractors, which would increase in the given environment, both the efficiency and output at a lesser cost. It was expected that the drawbar pull may be increased 15 to 25% and the coefficient of efficiency 10 to 15%. To this end V. V. Katsygin (1963 a) envisaged among others:

- further development of soil-machine mechanics
- further study of a theory of optimization of pertinent parameters
- elaboration of experimental problems and techniques of parameter optimization.

Computerization and Specialization

In the same volume (Trudy, TsNIIMESH, 1963), Lurie presented excellent tutorial material on "statistical dynamics of agricultural aggregate machines (generalized harmonic analysis) which was paralleled only in Germany by Wendeborn and the others (see Bekker, 1969).

Thus, mathematical modelling of the systems became more and more fashionable. Bel'skii (1963, of Frunze Politechnic Institute worked on speed analysis of a vehicle under variable rolling resistance. Another example of the same category of endeavor is a paper by Antonov (1963) on mathematical modelling of the stability of cross-country vehicles, and an article by Akhmedov (1963) from the Institute for Advanced Transportation Problems, Gosplan, on a computerized method for determining tractive capabilities of a vehicle. The theoretical basis for experimental evaluation of suspensions for cross-country vehicles was published by Yatsenko and Prutchikov (1963). Energy losses in, and the wear of , tires were investigated as factors affecting coefficient of efficiency of a wheel, by Kananykhin (1963).

Obviously, more computers were needed. Thus Rotenberg (1963) published another tutorial-promotional article which anteceded a similar work in the United States (McKenzie, 1966), as far as the schematization of driver-vehicle system is concerned.

This milestone in Russian systems analysis, which was parallel in other aspects to studies performed in the United States (compare Pradko, 1962), was reproduced in the diagram, Figure 62. Rotenberg's paper was undoubtedly stimulated by the U. S. work, since he quoted Olsztyn (SAE 127, 1960), Beauvais (SAE No. 295, 1961), Milliken (SAE No. 205, 1960), Bischoff (Autom. Ind. Nov. 15, 1960, Louden (SAE No. 169, 1960), Setz (SAE Journal No. 10, 1960), Staffeld (SAE No. 127, 1960), Hogt (SAE Journal No. 8, 1960), and Kohr (SAE 114 A, 1960), in addition to two German and four Russian papers.

Beyond doubt, the Russians were behind the West, in 1963, in the field of computerized programs, though they had at hand all the intellectual tools which we call software. What they were lacking was the hardware.

Nevertheless, statistical evaluation and statistical models of terrain-vehicle dynamics were processed with growing emphasis (Pevzner et al., NAMI, 1964; Pevzner and

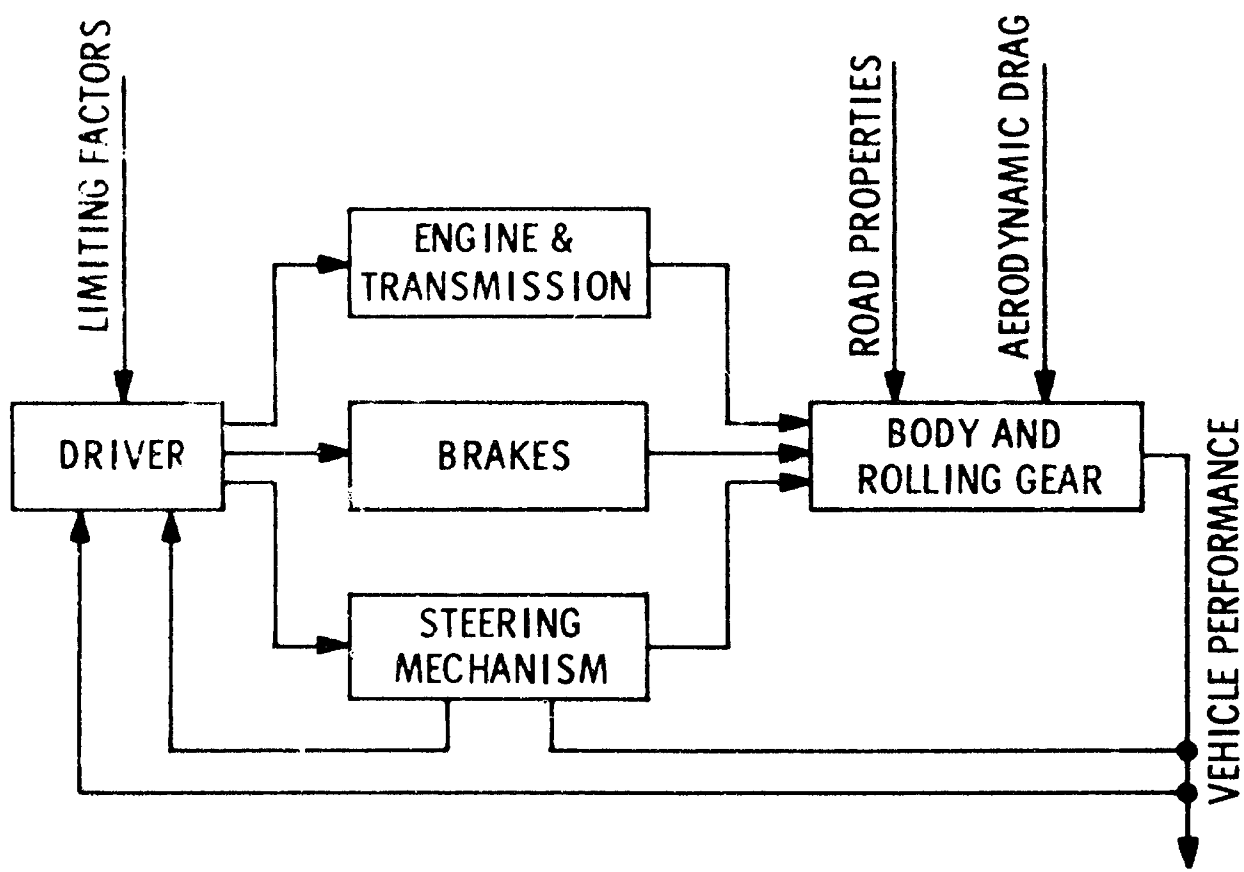

Figure 62 Rotenberg's (1963) vehicle-driver model

Tikhonov, NAMI, 1964; Parhilovskii and Zaitseva, Gor'kovskii Avtozavod, 1964). This also prompted gathering of statistical information for the data-bank (Armaderov et al., NAMI, 1964; Smirnov et al., MVTY-Bauman, 1964).

On such background the reappearance of a search for better soil value measurements, particularly from the agricultural viewpoint, is of no surprise (Voprosy... 1964, Vol. XIV). There was not much new, however, in this search that would change the picture of activities reported in Chapter II and Chapter IV; but the revival of the old problem was significant.

An excellent book by Ul'yanov (1964), on improvement of mobility and traction of wheeled tractors, again reproduced "in extenso" Bekker's (1959-1960) soil-value system philosophy, and the bevameter technique including exact copies of pertinent drawings. No direct reference in that respect was made in the bibliography. Instead, Frenkin (1962) who published the Russian translation of Bekker's work was referred to, among others, only Russian references. The book represents a pragmatic approach in mathematical modelling of a vehicle-terrain system, from the engineering viewpoint.

Specialization of mathematical modelling of design-performance complex, and data-bank assemblying, also may be seen in a unique book by Khachatryan (1965). The problem which he tackled was the evaluation of work of agricultural machine aggregates on a very uneven terrain surface. Among the topics of the first chapter were such items as:

- trajectory of motion of a free tracked tractor on slopes
- trajectory of motion of a steered tracked tractor on slopes
- tractor motion on variable contours of slopes
- characteristics of slope turns.

The approach, based on theoretical premises of tractor steerability and design parameters, was closely monitored in the field. A special instrument for marking the trajectories along the road was devised so that the estimated vehicle performance could have been compared with the real one (Figure 63). The significance of this work in system analysis, which reflects peculiarities of the environment, cannot be overestimated. Another example of in-depth treatment of the problem is the book by Brylov and Grabchak (1965) on transport equipment for geological survey.

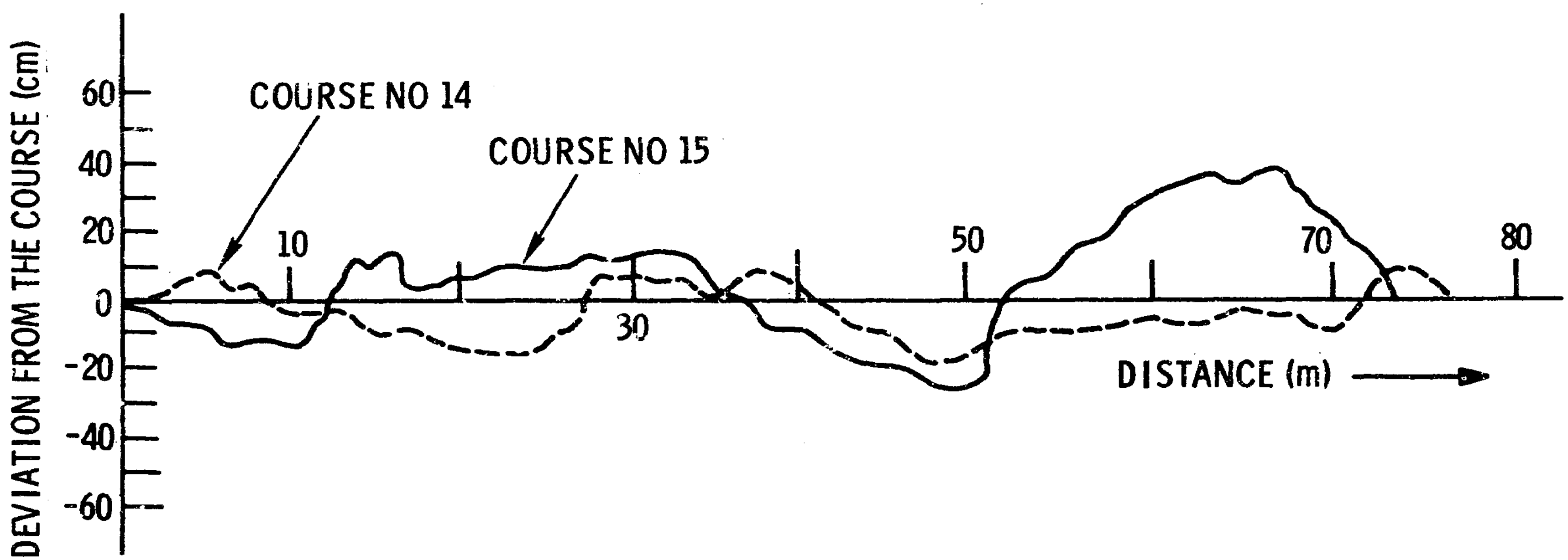

Figure 63 Controlled Trajectories of Motion of a T-75 Tractor on Winding Slope (Khachatryan, 1965)

However, the computerization of evaluations seems to have always been the main target. Hence, Rotenberg (1965) further thought of the method of evaluation of man-vehicle-road system. In addition, he performed original work largely based on American and German references. Of interest may be Figure 64 which shows system performance (curve 2). Though no details were given, Figure 64 hopefully exemplifies the nature of work performed. In the same realm, Parkhilovskii (1966) contributed to defining ride comfort for man-vehicle-road systems.

Special methods for computation of diagrams representing time-speed of locomotion were proposed by Degtyarenko (1966) of Rostov Institute of Technology. Incisive analysis of fuel consumption as a function of drive type for a 6x6 vehicle on hard road was provided by Filyushkin et al., of MVTU and NAMI (1966). This kind of a study exemplifies a specialized analysis of a subsystem, as discussed in reference (Bekker, 1969).

Obviously such specialization of the problems necessitated more computerization. Cherevan et al. (1966), of Zaporozhskii Institute of Technology (ZMI) named after Chubar, dwelt on computer programs for evaluation of vehicle dynamics, while Afanas'yen and Khachaturov (1966) of Moscow Automobile Institute (MAI) expanded this study with power spectral density analysis, and a study of pertinent electronic filters.

The high level of analysis-in-depth and of the computerization culminated in the collective work under the editorship of Akademician V. A. Zheligovskii (1967).

Differential equations of agricultural machine aggregates for a variety of operations with the purpose of defining:

- theoretical principles of increasing working speeds of the aggregates,
- time utilization in aggregate's operation,
- output and economy at higher speeds,
- targets for speed increase and the methods of their meeting, and
- mechanics of soil working,

where the topics related to locomotion. Materials such as that, and the book by Guskov (1966) about the optimization of tractor parameters, represent a good sample of the Russian "software" waiting for more computers. The software that has not

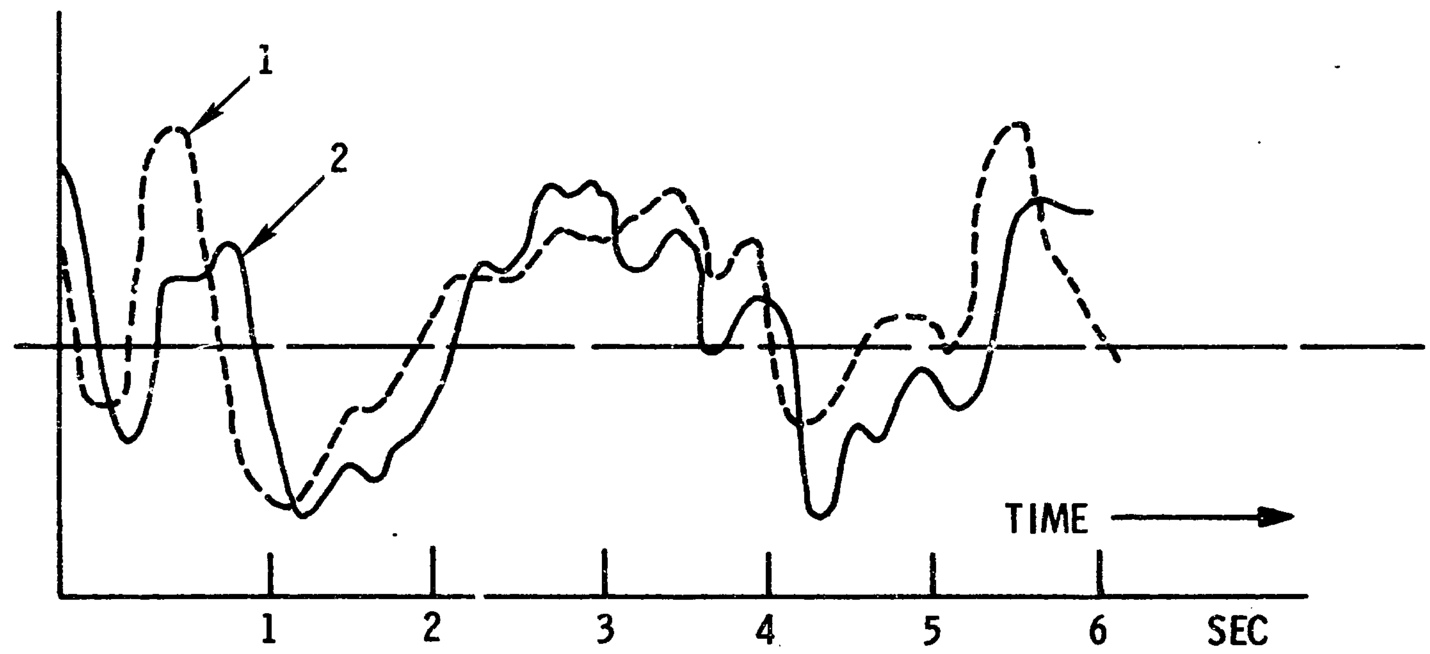

Figure 64 Test results of a man-machine system. Curve 1 describes system's performance; curve 2, man's performance. (Rotenberg, 1965)

yet been produced in the same quantity as in the West, although computers on this side of the world either idle or process rather academic off-road locomotion problems.

Obstacles to Progress

At this stage the obstacles facing Russian scientists and engineers may be discerned clearly. Apart from the multitude of Research Institutes, which create enormous problems of communication, the insufficient coordination, the red tape, and the lack of computers appear to be a very serious hindrance.

According to one estimate there are 5,000 working computers in Russia, compared to 50,000 in the United States; in addition, the still unsophisticated "Minsk" (see Guskov, 1966) does not compare with the superb, fourth generation American equipment. As Andrei Sakharov (1970) put it "the gap is so great that it is impossible to measure it. We simply live in another epoch."

Obviously, the severity of the situation depicted by Sakharov does not apply to research in off-road locomotion. Sakharov was concerned with the "big science," and was correct. In the "small applied science" such as the disciplines related to ground locomotion, computer sophistry is not much of a need. Undoubtedly, a "Minsk" may well suffice if there are enough of them.

Perhaps, what also hampers progress in Russia is the lack of established methodology of system analysis, such as that used by American aerospace industries, and the lack of an appropriate managerial class. As a matter of fact, Russia's first management-training school was not opened until late in 1969 (Newsweek, 1970).

Nevertheless, the ingredients and potential to overcome all of these difficulties do exist. Moreover, as this study has implied, the mass of Russian mathematical modelling, of the databank information, and above all, of the trained, high caliber researchers, is such that they counterbalance the bureaucratic ineffectiveness, and may quickly catch up with and surpass the rest of the world, as it has been demonstrated in several other fields of science and technology. This kind of a "miracle" has already happened with the help of others, when Fiat of Italy built in Russia the first modern, mass production automobile factory.

According to Berliner (1969), Soviet planners are already worried. "In a move which could have major implications for capitalist economics, Soviet leaders have enacted a series of reforms." If they succeed, we will suffer in the realm of ground locomotion a prolonged setback because of the lack of inputs to our computers, and the scarcity of manpower trained in ground mobility research.

More "Software" and Some Hardware

Whatever will happen, the Russian engineers and scientists are further building those inputs and expanding their "software."

Thus a morphological study with a touch of dimensional analysis was published by Kav'yarov and Pozin (1967) of ChTE.* Interestingly, the data encompass Russian and Western equipment. Stabilization of steering wheels and their study with analog computers was discussed by Tchaikovskii (1967). More on subsystem analysis, in the vein of reference (Bekker, 1969), was produced by Smirnov i Lelikov of MVTU (1967). Figure 65 reproduces competitive drive subsystems of an 8x8 vehicle that were subjected to mathematical modelling for the purpose of optimizing certain aspects of vehicle performance.

Simplified method of computing average speeds of a vehicle, based on statistical analysis of speed distributions in a variable terrain, was given by Ivanov and Uvarov (1967); and a "dynamic index" definition of a vehicle, considering properties of the wheel drive, was proposed by Petrushov of NAMI (1967). Both papers represent models of performance, useful in system evaluation.

Computer programming also has not been forgotten. Sirotkin et al. (1968) produced an electronic model of the hydraulic transmission of automobile Bel AZ-540 based on differential equations showing a rather unusual agreement between the experiment and computer results (Figure 66). Medvedkov and Yar'kov (1968) wrote on the application of computers to the evaluation of a "speed regime" of vehicle motion. Again the mathematics was followed with electronic block diagrams and the computed results

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* The acronym not identified.

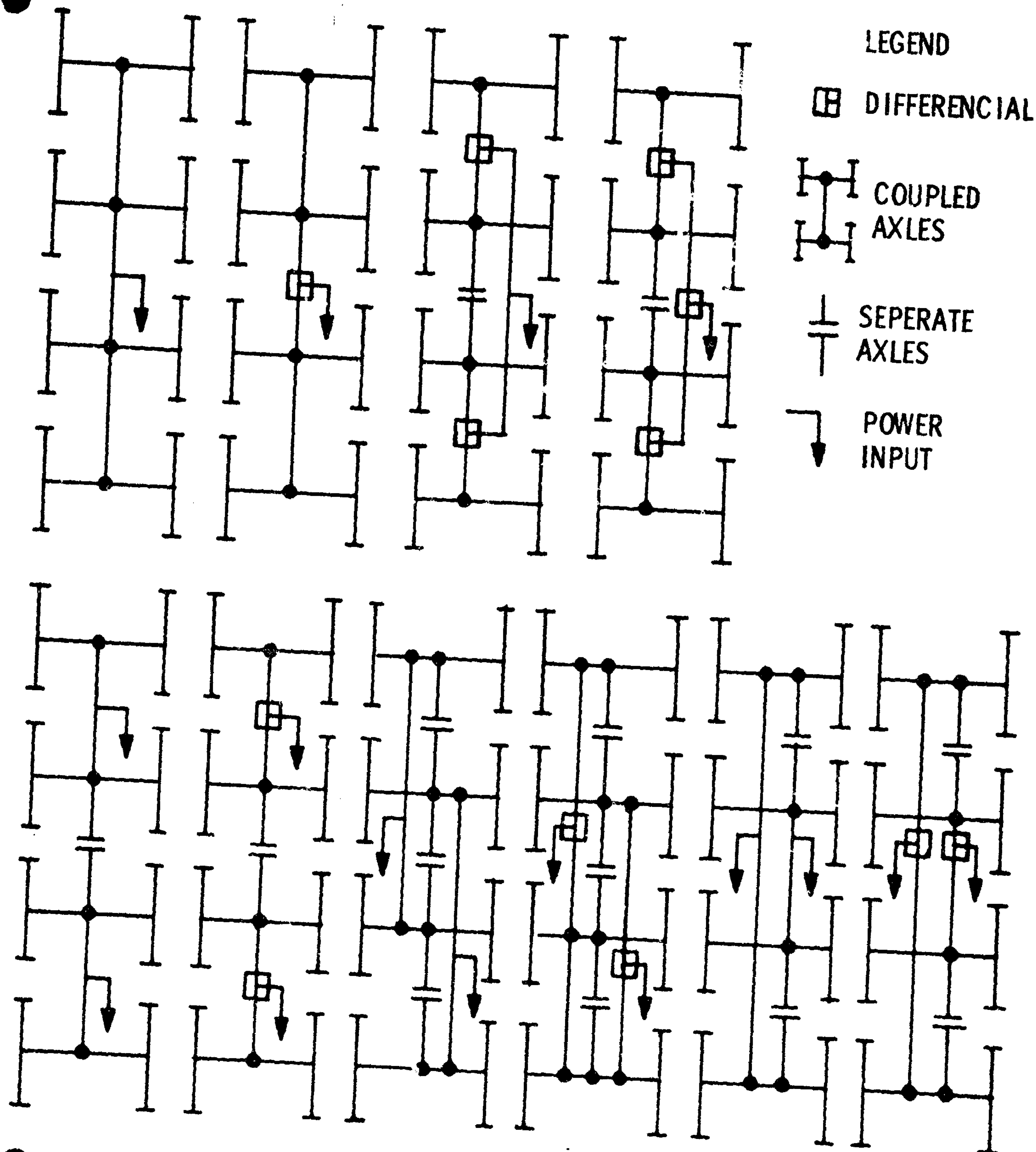

Figure 65 Possible "candidate" drive line subsystems for an 8x8 vehicle (Smirnov and Lelikov, 1967)

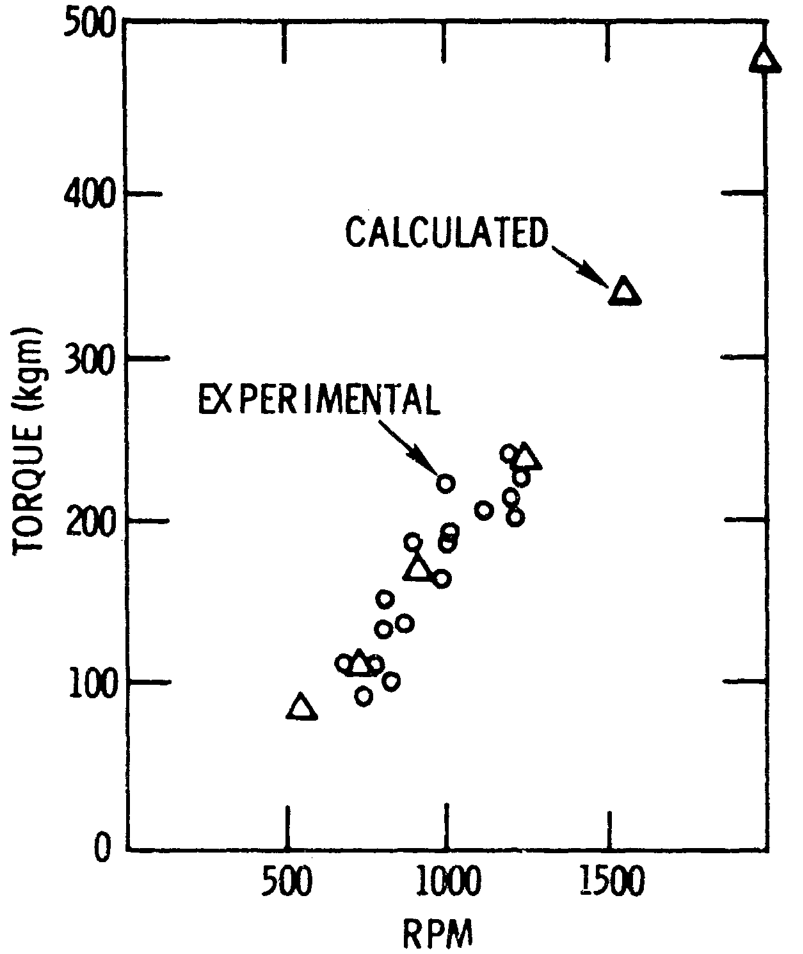

Figure 66 Torque-rpm for the first gear of Bel AZ-540 vehicle, as predicted and tested (Sirotkin, et al., 1968)

were tested with excellent accuracy (Figure 67). Tsimberov (1968) also dwelt on computerized methods of evaluation of ride comfort of a vehicle and provided methodological framework for assessment of vehicle stability from the viewpoint of driver's reaction. Previously quoted work by Rotenberg and Janeway and Dieckmann also were referred to (for details see references in Bekker, 1969).

An interesting part of this study is the scheme of a vibrator for testing man-machine relationship, which outwardly resembles equipment used in this country since about 1962. The scheme is shown in Figure 68. According to a laconic description, the instrument consists of a computer that processes data and reproduces vibration parameters in "natural scale," which are subsequently recorded on a magnetic tape.

Vibration generator produces simulation which was explained as follows: A preprogrammed signal actuates the vibration source and hence the suspended portion of the stand. This element draws energy from the variable magnetic field. Displacements (amplitudes) of the vibrated object (or man) result from the interaction of magnetic forces between the stator and the suspended elements of the machine. Thus it would appear that the energy was not applied through hydraulic actuators, which necessitated generating large magnetic fields.

In another article describing a different test stand for the study of a man-vehicle-road system (Gaitsgori et al., of VNII Stroidormash, 1969) hydraulics were unmistakably used (Figure 69). Here, more details were given, including the electric and hydraulic schemes of the instrument: vibration noise generator 1 simulates road input; analog computer 2 processes vehicle's transfer functions; recorder 3 provides the history of the vibrational process which is actuated hydraulically through electronic valves 4 and 5 mounted on frame 6.

Computerized methodologies of vehicle evaluation necessitated more mathematical modelling. The year of 1968 and 1969 were more prolific in this sense, than any previous year. This is indicated by the following review of the representative sample.

Kuznetzov (1968) of the Transport Research Institute (NIAT) devoted more thought to the economics of vehicle use. Reliability, which could not longer be considered beyond the system, was subject of a study by Indikt et al., from NAMI (1968). Their work was related to accelerated tests on the proving grounds, which were analyzed by Rumenkov (1968).

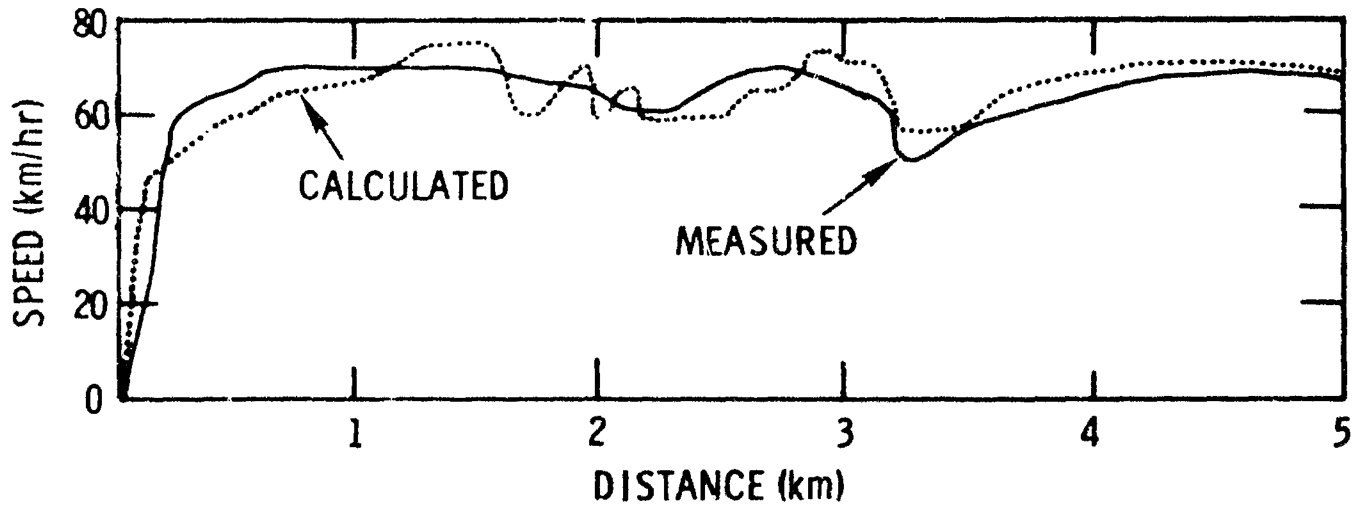

Figure 67 Calculated and measured speeds of 5 ton gross weight vehicle (Medvedkov and Yar'kov, 1968)

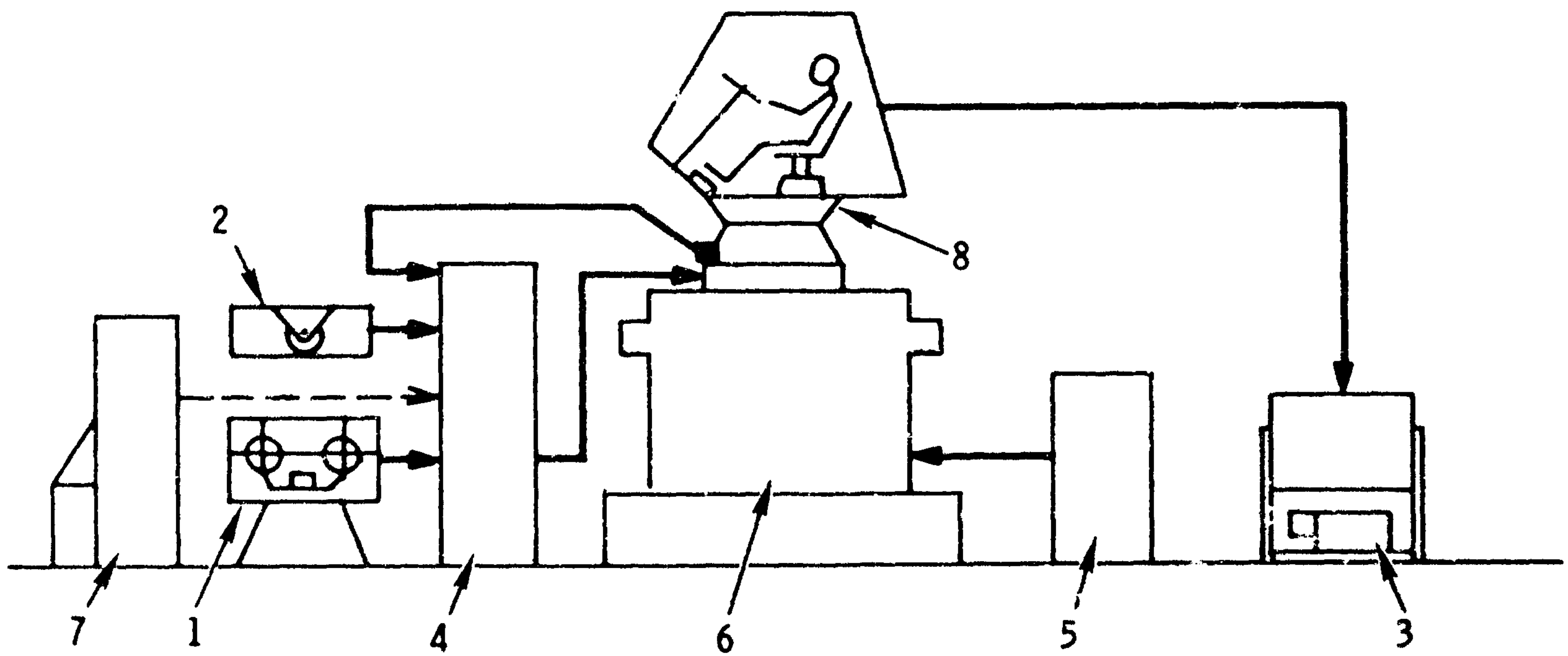

Figure 68 UEDC-1 Electrodynamic stand for investigation of man's response to vibrations. 1-Magnetic tape recorder; 2 - signal generator; 3 - controls; 4 - power vibrator feeding energy into the suspended part of the stand; 5 - power vibrator actuating unsuspended excitation system 6; 7 - computer; 8 - suspended portion of the stand (Tsimberov, 1968)

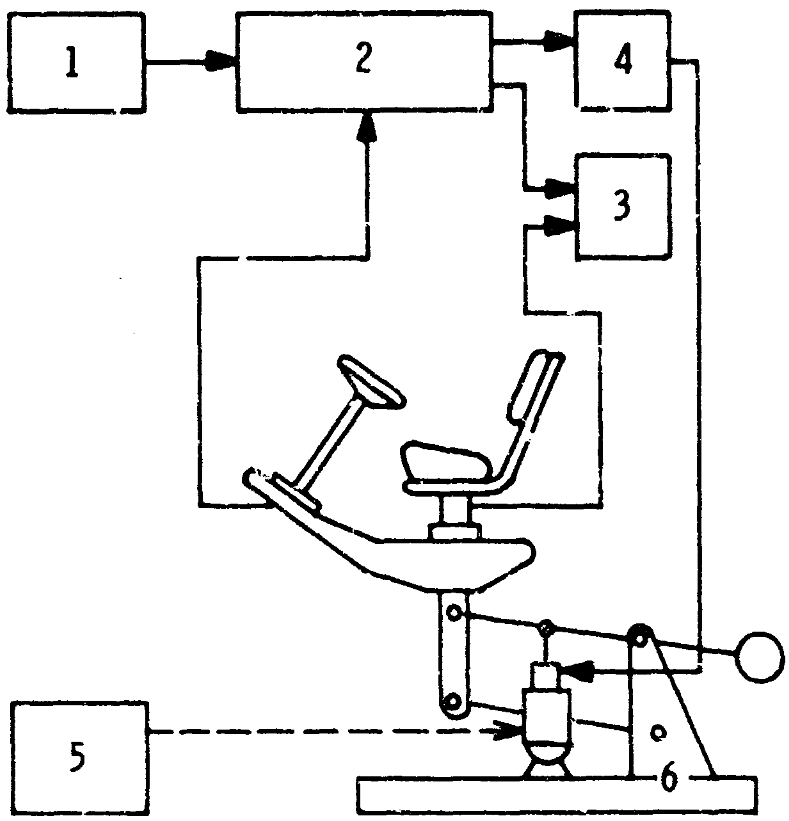

Figure 69 Test stand for a "study of road-vehicle-man system" after Gaitsgori, et al. (1969)

Since much emphasis has always been put on the economy and saving of natural resources, mathematical models that would help such savings were very popular. Accordingly, Genbom et al., (1968) of Lvov Institute of Technology developed an analytical method for vehicle economy. Knoroz et al. (1968) wrote in a similar vein. Two studies by Guskov (1968, 1968 a) optimized rolling resistance and design parameters, hence tractor economy. Interestingly, both were in a sense a reiteration of the 1966 and prior analyses. But they were published in English, for the first time.

The significance of this move is subject to interpretation. In any case, the Russians would not display anything which they did not consider superior to the state of the art in the West. And the theory reported by Guskov (1968) showed, in his own words, that:

- "for each tractor class... there is an optimum of (design) parameters which provide the highest drawbar performance and tractor efficiency.
- The optimum parameters... can be determined theoretically;
- theoretical considerations and experiments have shown that as the tractor size (nominal drawbar pull) is increased, the traction coefficient and efficiency are reduced."

These are significant conclusions. Whether they are new or not is immaterial, at this point. What matters is the fact that the Russians have a theory (Katsygin and Guskov, 1968) which has not yet been paralleled by the others.*

Theorization on a concept basis involved more morphological vehicle analysis and form-performance studies (Reznikov of NAMI, 1968; Aksenov and Poliakov, 1968; Korotonoshko, 1968). Works of this type embraced among others a systematic study of vehicle configurations, which was performed in the same style as the study of transmission subsystems shown in Figure 65.

* However, the British and German work cannot be neglected. As a sample of the fine analysis parallel to the Russian work, see Gilfillan (1970).

Of particular interest in this area is the scholarly work by Smirnov and Izvozchkov (1969) of MVTU, which contains a fine mathematical analysis of drive schemes (Figure 65). In the same vein, Koltsov et al. (1969) of the Moscow/Motorway Institute (named after A. N. Ostrovtsev (MADI)) wrote on mathematical modelling of elastic wheels for fast changing loads; and Nofikov and Taipov (1969) of Bashkirskii Agricultural Institute gave a fine dynamic model of a tractor-agricultural implement aggregate. Stolbov and Kopelevich (1969) of Krasnoyarskii Agricultural Institute investigated speed effect upon tractor effectiveness.

A similar trend toward considering larger and larger machine-environment systems, and toward their mathematical modelling, has been seen in Poland, where Soltynski's 1966 book was significantly entitled "Mechanics of Terrain-Vehicle Systems." Wislicki's (1969) booklet is perhaps the first systematic theoretical study of a tractor-bulldozer-soil system based on experimental verification. Grencenko's (1963) book on tractors is more conservative but nevertheless very emphatic on mathematical modelling (compare Grencenko, 1968).

On this background it is necessary to quote the Russian book by Vasil'ev et al. (1969). This latest publication, which referred to works by TsNIIMESH, NATI, NAMI, VIME and to... " foreign works (among which) the greatest interest is attracted by works of M. G. Bekker..., " is a perfect example of the prevailing Russian school of thought as described here. Mathematical modelling of vehicles based on carefully planned experimentation, soil-values, databank, and experimental verification of results were described in an original contribution by the writers. Foreign references, in addition to Bekker (1965 and 1960), included Kuether (Farm Equipment and Machinery, March 1966), Ogorkiewicz (1961 and 1962),* and Schlor (ATZ, July 1959).

Among the topics discussed in separate chapters were:

- method of an experimental study of the effect of design parameters of a tracked tractor upon its traction
- results of experimental study, mentioned above

* Ogorkiewicz popularized the work performed in the U. S. Land Locomotion Laboratory prior to 1960 (for details see Bekker, 1969).

- results of an experimental study of track-soil relationship
- theoretical generalization of experimental data from the viewpoint of the effect of design upon motion resistance
- theoretical generalization of experimental data, from the viewpoint of the effect of design upon traction.

A book on the theory of automotive soil-working machinery by Ul'yanov (1969) represented the same school, at its best. It referred only to the Russian authors, though as mentioned in Chapter V it was not free from the Western influence. Among the topics related to off-road locomotion, the following were discussed:

- Characteristics of physico-mechanical properties of the ground
- Theory of a pneumatic-tired prime mover
- Experimental study of prime movers with pneumatic tires
- Design for subsystems of soil-working machine aggregates
- Traction and work output, analysis, experimentation, theory
- Speed, vehicle dynamics, effectiveness
- Engineering of equipment
- Morphology, economy, and effectiveness of various types of machinery.

Agricultural works were typified with the same trend. In Volume VI of the "Trudy" (1969), various authors were concerned, among others, with the following themes:

- Energetics of tractor-machine aggregates
- Economy of agricultural tractors in different soils
- Speed versus efficiency of tractors
- Selection of parameters in a 4x4 drive
- Statistics of load regimes in agricultural vehicles.

"Zemledelcheskay Mekhanika" Vols. X and XI (1968) reflected more generalization of system analysis with such chapters as:

- Criteria used in projecting process effectiveness
- Optimum programming of agricultural systems.

This was close to the operational research without which a systems analysis can hardly be used. Accordingly, a collective volume on mechanization and electrification of agriculture (Mekhanizatsya i elektrifikatsya S-H, 1968) dwelt on such topics as:

- algorithms for determining optimum tractor-machine mix
- planning of utilization of a tractor-machine mix with nomographic methods, etc.

A high level operations research, plus systems approach, was made by Akademician Vasilenko (1968), who outlined a general mathematical theory of optimum solutions for agricultural technology. In the same volume, however, Novichikhin (1968) presented a fine engineering evaluation of soil strength based on Letoshnev, Katsygin, and Saakyan definitions that were disucssed earlier. A similar methodological approach was made by Strokov (1968) to the problem of increasing vehicle mobility. This combination further illustrates the search for "software" with an almost complete lack of activity and material based on actual computations by the electronic "hardware."

The late nineteen sixties were the years of book publishing. The predominant theme was the system, the integrated value complex, economy, operational research, and process evaluation, all based on mathematics.

Saakyan (1969) in his book on a "system of indices for evaluation of complex mobile machine aggregates" distinguished between "factors, exponents, and indices." The popularity of this approach may be seen in numerous references which were tabulated, starting with Academician V. P. Goriachkin, who apparently was the first one to try to classify and group various types of indices.

The discussions verge on generalities and may appear sometime as half political:

> "System of indices is defined as a scientific, well founded interlocked assembly of indices which assess the machine from the viewpoint of national effectiveness,"

said Saakyan before classifying the indices into:

- natural, such as weight, dimensions, a, b, c;
- specific, such as ratios, a/b, b/c;
- relative, such as (a-b)/a or (a-b)/b.

What the "national effectiveness" was has not been defined. However, extensive tabulations of "agrotechnical indices" and others show a strong drive toward bringing

some order and sequence into the whole value system. Tabulation of "indices" defining physical properties of a processed "material" is shown in Figure 70.

The block diagram reproduced as Figure 70 displays a generality, which was subsequently treated in detail, in a rigorous manner. The book applies operations research methods to the increase of agricultural output in which tractor-machine aggregates play a decisive role. The author went so far that he even included "esthetic-ergonomic" factors as a part of the system.

In contrast to this broad approach to a very broad problem, Ostrovtsev (1969) wrote a book on rollers equipped with pneumatic tires. Although this was a handbook for design-evaluation and concept selection for multi-wheel agricultural implement, an attempt at treating the problem from a systems viewpoint was clearly distinguished. Figure 71 shows the tabulation and classification of possible solutions. It has been reproduced without translation, since the technicalities of the problem are immaterial to the context of this study, and might obscure the broadness of Ostrovtsev's approach.

As mentioned before, terrain-vehicle system evaluation without generalized soil-values is virtually impossible. A broad attempt of defining the Russian state of the art was thus made by Bakhtin (1969) of the All Russian Academy of Agricultural Sciences, named after Lenin. The book discusses most of the methods of soil measurement and instrumentation described in Chapters II, III and IV, in an apparent attempt to clarify the issues and to compare various methods. Unfortunately, this was not necessarily done from the locomotion viewpoint but from the agricultural and soil classification viewpoint.

Nevertheless the book shows that as late as in 1969 the soil-value problem was still an issue – this time, however, a very broad one, embracing the whole system (Figure 70)

In the same vein, and practically at the same time, Revuta i Rode (1969) wrote a book on a study of "Soil Structure." It also was devoted to the tutorial-critical review of the state of the art in agricultural soil measurements, as reviewed in Chapter IV. Again the problem of locomotion was a microscopic part of problems related to soil-physics and soil mechanics, treated from the agricultural viewpoint. The bibliography

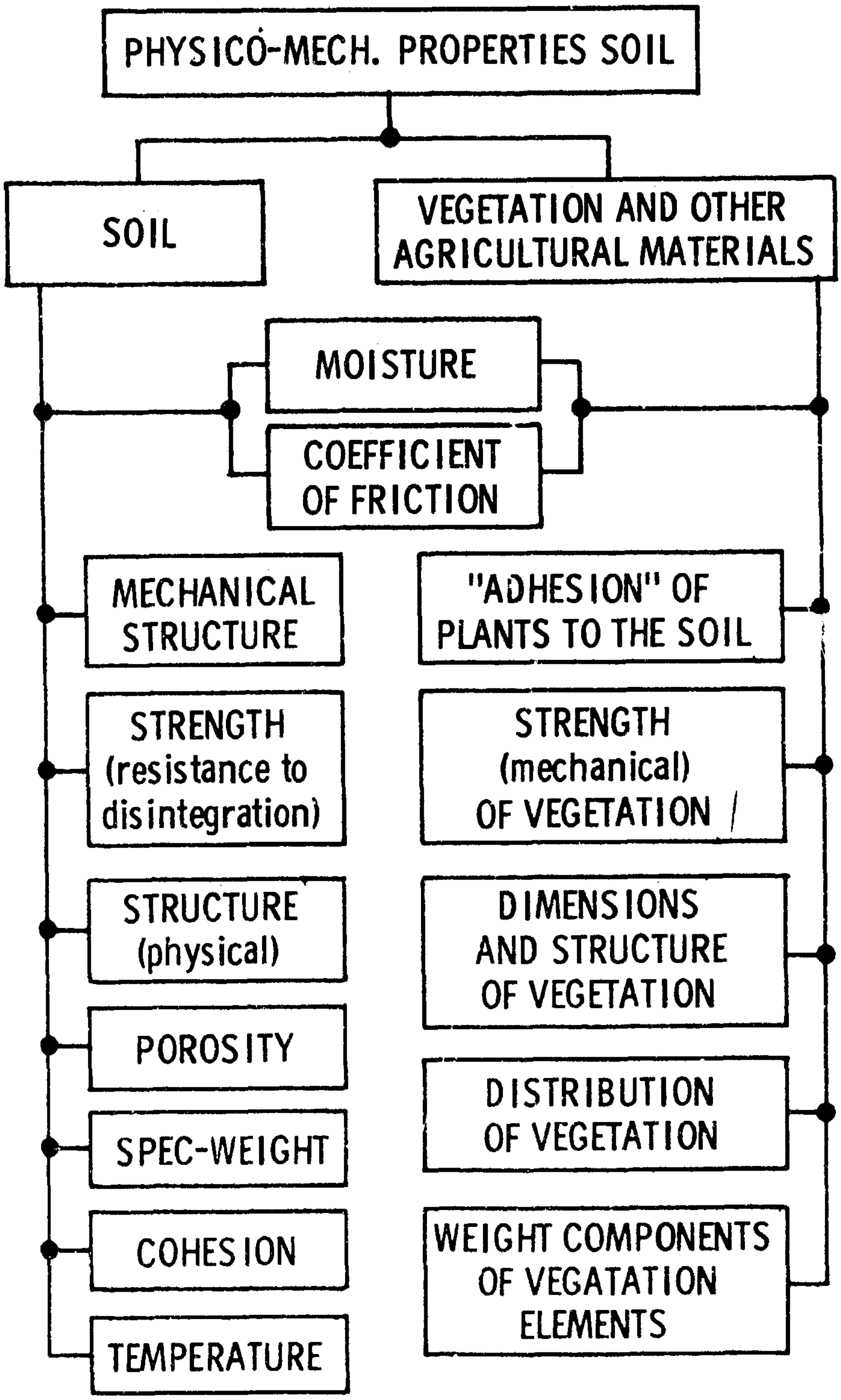

Figure 70 Block diagram of physico-mechanical properties of materials used in agriculture (Saakyan, 1969)

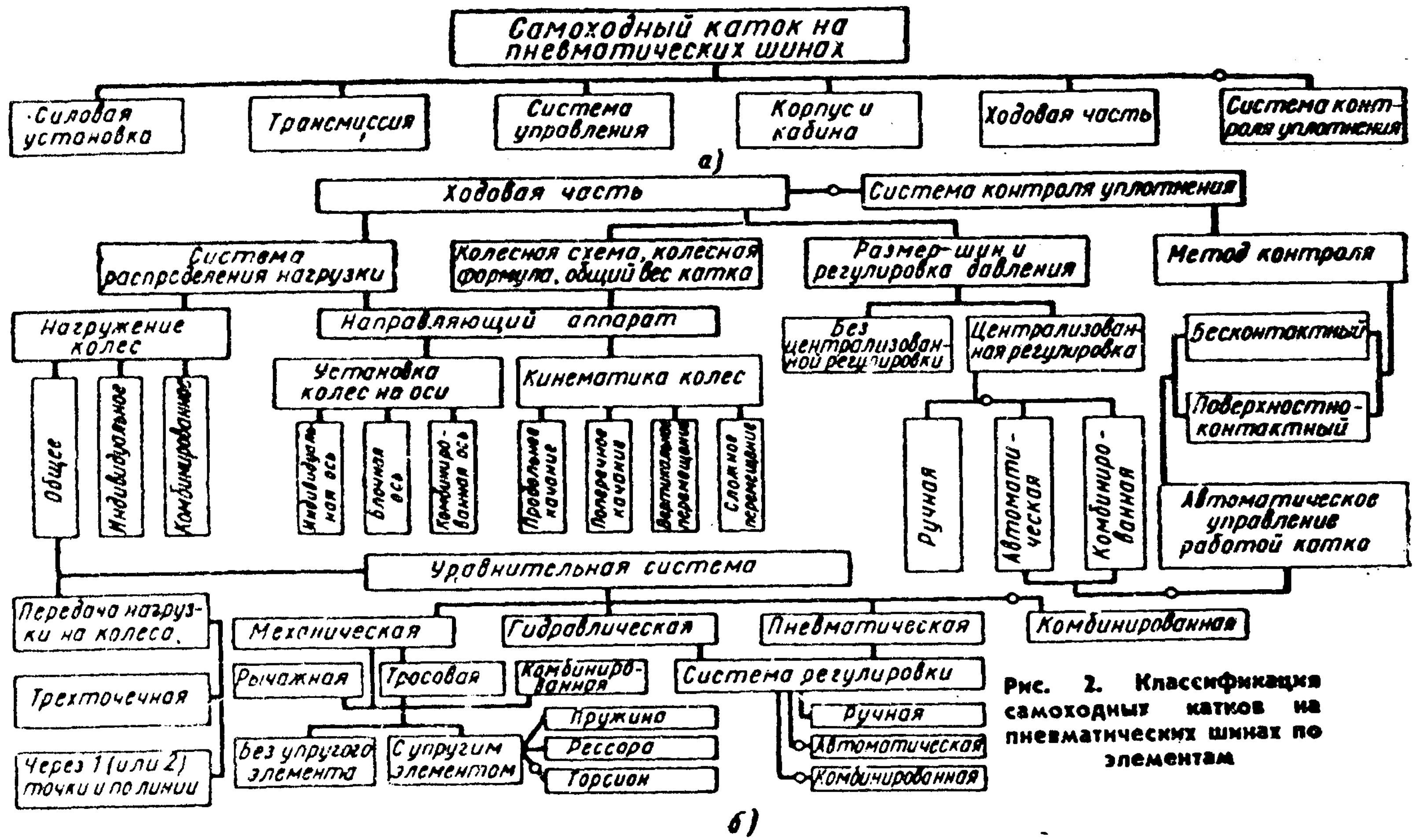

Рис. 2. Классификация самоходных катков на пневматических шинах по элементам

Figure 71 Classification of rollers on pneumatic tires for use in agriculture (Ostrovtsev, 1969)

was very extensive (88 entries) and included, besides the Russian, many German, Czech, Polish, Italian, Rumanian, Hungarian, and French references. The absence of British references was beyond explanation. Only one American reference (Bekker, 1960) was quoted. The book showed again the uneasiness of the Russian scientists and engineers with the prevailing crude empirics and with the lack of a soil-value system.

This feeling was undoubtedly a cause for the publication of another book. The work by Bakhtin et al. (1969) printed under the heading of the USSR Academy of Sciences undertook the difficult task of collecting a variety of physico-mechanical soil properties and their variations for a number of Russian territories. The book was conceived as an aid to evaluation of performance of agricultural soil-working machinery, without, however, telling much about the applicability of this databank to tillage, ploughing, etc.

In another book on research and development of machines for earth works, edited by Fedorov (1969) under the auspices of the All Russian Scientific Research Institute for Transport Technology (VNIITS), the authors proceeded with the best available soil knowledge and developed equations and computerized programs for optimization of performance and design parameters of single-bucket loaders. This was quite an advanced study, as may be deduced from the block-diagram of the computations (Figure 72).

More on systems approach was published in the English language in a brochure by Tolpekin (1969). Figure 73, reproduced from that publication, speaks for itself. The original English text was slightly edited in order to make it more clear without changing the basic verbiage. It seems that in this material – undoubtedly of a promotional-advertising nature, destined for foreign consumption – the computerization techniques were still behind even the slightest sophistication.

Thus ends the review and analysis of Russian literature published up to 1969.

The Present Structure of the R&D Effort

This review could continue with 1970 literature. This would provide, however, only a repetition of the argument presented in the preceding sections, to the effect that

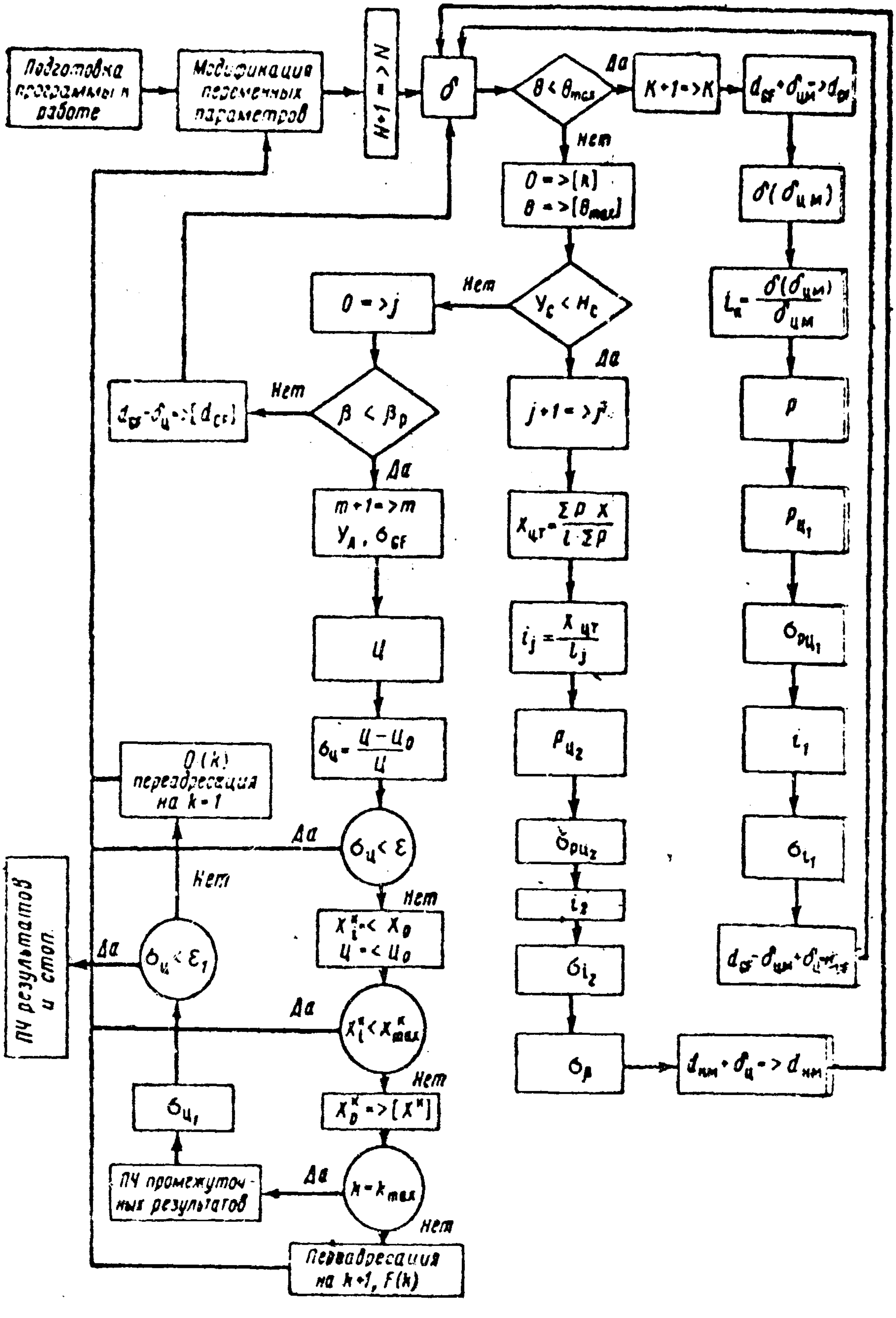

Figure 72 Block diagram for computation o˙ the optimum parameters of a single bucket loader (Fedorov, Ed, 1969)

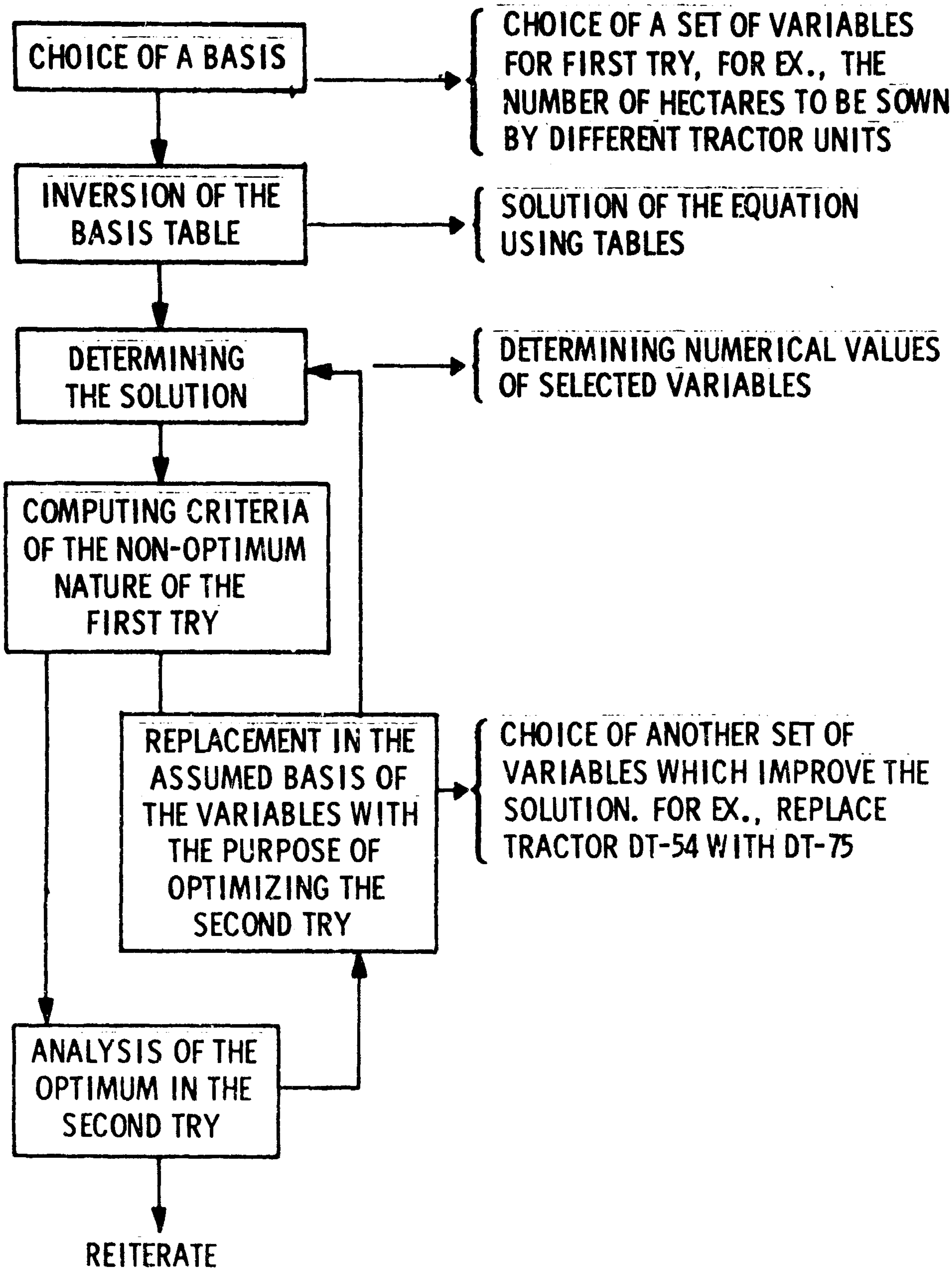

Figure 73 Optimization of an Agricultural Operation Involving Tractors (Tolepkin, 1963).

Russian engineers and scientists, though handicapped by the lack of computers, have been developing in depth a theoretical basis for computerized systems analyses; and their databank, mathematical models, and subsystem analyses have been based on sound experimental practice of automotive, agricultural, and mechanical engineering.

Thus in this section, instead of reiterating these conclusions by a chronological review of literature, another look was taken at the Russian R&D effort, as seen through their work published in 1970.

In the preceding sections, an attempt was made to show how early parametric analyses developed into more mathematical modelling of simple vehicle-environment-mission complexes, and then helped to formulate a philosophical basis for system analysis; and how all this culminated in the rather simple computerization of the process of optimization. It also was shown how the difficulties inherent in the Russian way of doing business hampered progress in computerized techniques, leading to a concentrated development in depth of what we generally call "software."

As a consequence it now appears that a closer look upon this "software," taken on the background of 1970 publications, may be of interest, since it may reveal the structure of the Russian R&D in more detail.

To this end the most representative journals, the Avomobilnaya Promyshlennost and Traktory i Selkhozmashiny, were selected. To compare these publications with similar material available for public consumption in this country, the ASAE Proceedings and the Agricultural Engineering magazine were selected together with the SAE Journal (later called Automotive Engineering) and the SAE papers published in 1970.

Articles used in this study pertained only to locomotion. They were classified into the groups listed in Table 28. Since many articles covered topics that fell into more than one category, they were listed accordingly.

As the interpretation of materials such as these may be misleading, the following should be stressed before drawing any conclusions from Table 28. The Russian work published in open literature is of a rather high professional quality. It is not concerned with

Table 28

Topics of Papers and Articles		Number of Entries: USSR: Traktory i Sel'khozmash	USSR: Avtomobilnaya Promyshlennost	USSR Total: Number	USSR Total: %	USA: Agricultural Engrg. & Proceedings	USA: SAE Journal & Meeting Papers	USA Total: Number	USA Total: %
General	Promotion, Soc. Polit.	9	3	12		11	3	14	
	Trend Analysis	10	4	14		4	1	5	
	Operations	7	5	12	31.0	2	6	8	32.0
	Production	14	17	31		1	18	19	
	Informational	15	10	25		7	11	18	
Mathematical Modelling	Veh. Dyn. & Statics	23	26	49		8	7	15	
	Man-Veh. Systems	1	1	2	27.8	3	3	6	24.0
	Computer Progr.	5	6	11	13.2	6	8	14	29.2
	Veh. Economy	7	3	10		1	2	3	
	Soil-Veh. Relationsh.	8	4	12		7	3	10	
Design and Engineering	Engines	27	11	38		2	22	24	
	Transmission	7	12	19		3	5	8	
	Running Gear, Susp.	4	7	11		3	5	14	
	Chassis	5	6	5	29.4	1	3	4	30.5
	Steering	3	2	5		1	3	4	
	Body	2	3	5		2	5	7	
Test & Experimentation	Road-Soil-Vehicle	7	14	21		7	7	14	
	Mech. Efficiency	6	3	9	11.8	3	4	7	13.5
	Fuel Economy	4	2	6		1	5	6	
		164	139	303	100	73	127	200	100

classified or "proprietory" information. The over-riding purpose of its publication apparently is to provide the forum for professional achievement and educational facility. This is why most of the editorials promote social and political aims. There is no commercial overtone or preoccupation with trivia. On the other hand, there is little if anything about safety and pollution.

American publications likewise do not contain classified and proprietory material. Their aim also is to provide a forum for individual achievement. However, their educational value and professional level are of a lesser caliber, because the over-riding reason for publishing many papers appears to be corporate publicity and advertising. An exception is the works on safety and pollution, where high caliber researchers often recruited from the universities and independent "think tanks" produce material far superior to the Russian materials.

For the purpose of this study, all the American publications on safety, pollution, electric power, standards, norms, vehicle components (ignition, carburetors, batteries, lamps, etc.), racing cars, trim, styling, etc., were eliminated. Since these subjects practically do not appear in Russian literature, at least not in such an abundance as they do in American literature, the total number of American themes related to off-road locomotion was 200 as compared to 303 Russian themes.

This leads again to an overwhelming conclusion that:

- The Russians publish more professionally superior material related to off-road locomotion, than we do.

Perusal of Table 28 indicates that the number of promotional material, mostly editorials, is even in both countries. However, the Russians publish more on trend analysis, which is in line with their expanding databank for system analysis. The same applies to the matters on production and information, which, in part, is self explanatory: their production is lagging far behind the U. S., but why they produce more informational material than we do is not quite clear. Perhaps they do what we "compensate" with advertising.

Russian studies on Vehicle Dynamics and Statics are overwhelming, both quantitatively and qualitatively (except for our safety work not accounted for here). However, our analyses of man-vehicle systems prevail. Computer programming is "à par" quantitatively. But qualitatively the U.S. work is far superior.

In this respect, one must also notice that, percentage-wise, American computer work takes 29.2% of the total effort in the mathematical modelling, while the Russians take only 13.2%, as shown in Table 28 by the underlined numbers.

Preoccupation with engines is similar in both countries. Transmission problems are more preponderant in Russia, together with chassis problems. The remaining questions of design and engineering are practically similar. Test and experimentation effort also is quantitatively similar; but its nature is different. In Russia more emphasis is put on collecting a generalized databank, while in the U.S. most of the work relates to a specific item under R&D.

Figure 74 shows the data of Table 28 plotted in the form of a graph. This graph was "rounded up" for clearer comparison purposes on Figure 75. Figure 75 and Table 28 show that the Russians mathematical modelling activity is almost double the Americans (84 vs 48 themes), although percentage-wise both are practically equal (27.8 and 24%). Note that in this comparison we lead in computer programming techniques (14 vs 11 entries) while the Russians lead in mathematical modelling of vehicle dynamics and statics (49 vs 15 themes) and in a search for vehicle economy (10 vs 3 entries).

This, it is believed, is the main strength of the Russian effort. For computer programming is a technician's work, while the establishing of good, reliable models and boundary conditions, and maximizing of the economy, is the job of a professional researcher in off-road locomotion.

To sum up, another look at Russian R&D effort leads to the same conclusion as the analysis performed in previous sections of this chapter; in addition it illustrates:

- the preponderance of theoretical approach based on sound engineering, and superiority in both quality and quantity of published material.

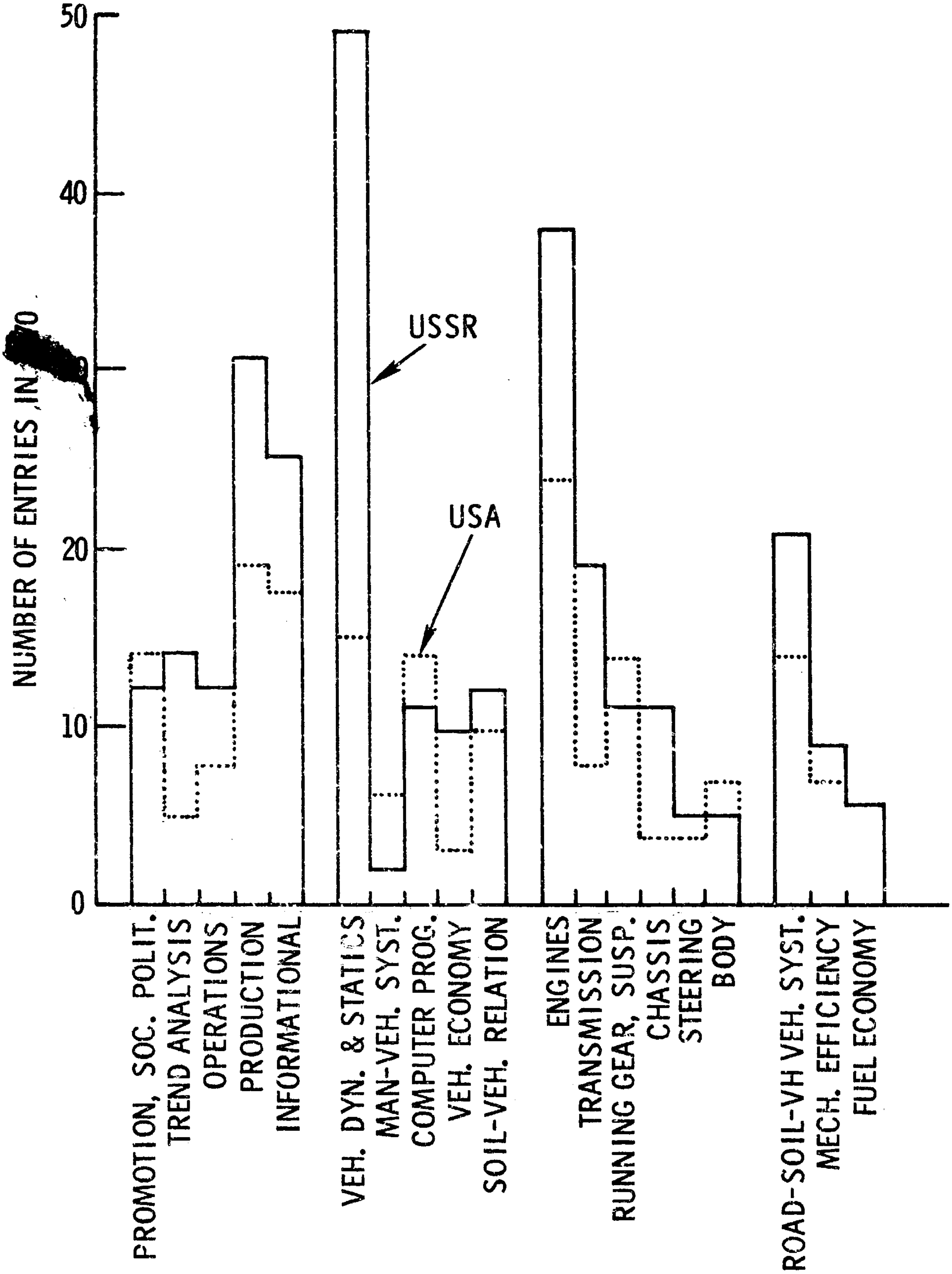

Figure 74 Approximate structure of R&D effort in off-road locomotion in the U. S. S. R. and U. S. A.

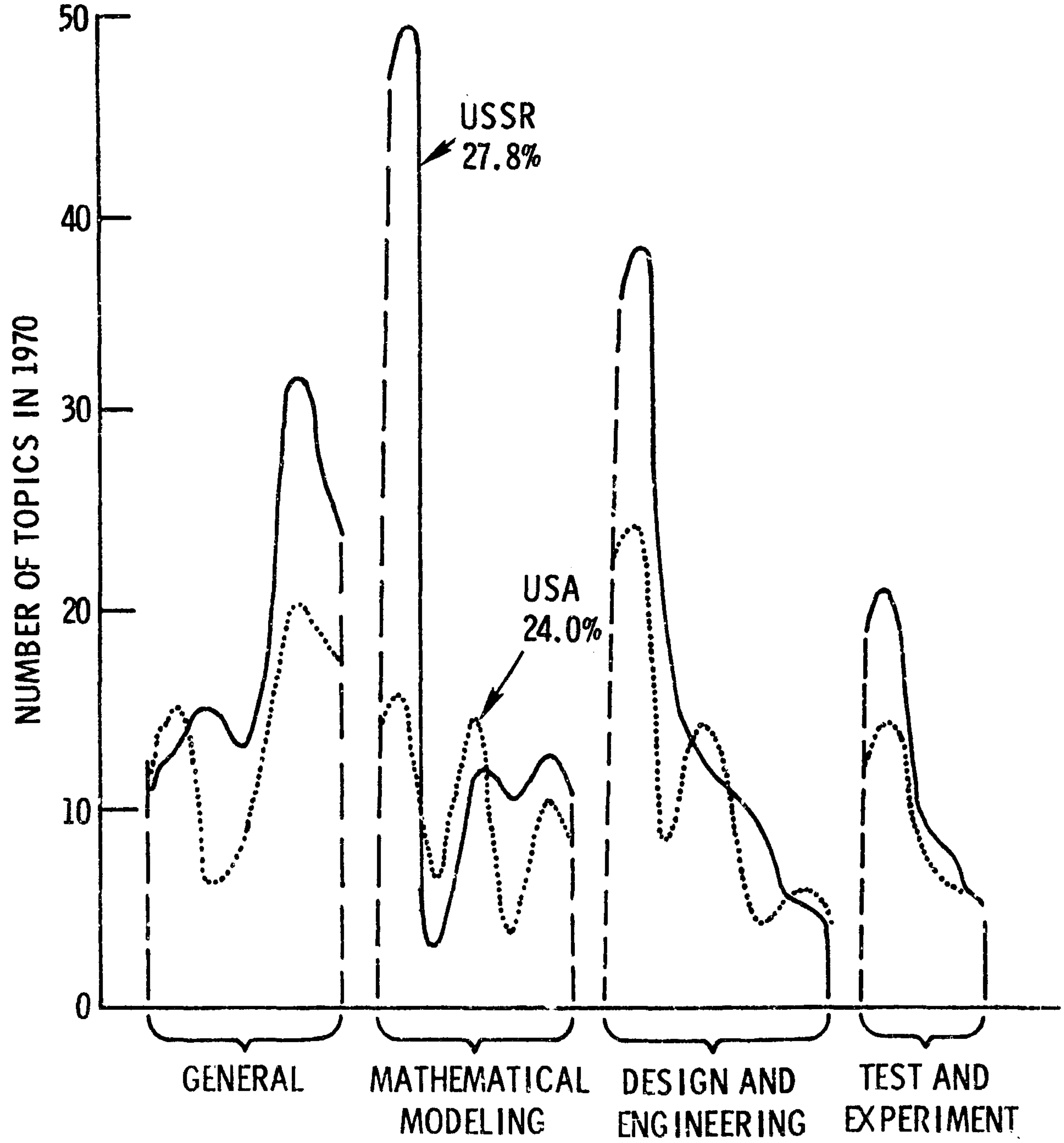

Figure 75 Approximate structure of R&D in off-road locomotion in the U. S. S. R and U. S. A.

To give the reader a sample of the quality of material reviewed by this writer, a number of 1970 articles is chronologically discussed below. The articles pertain only to mathematical modelling and computer procedures, since the remainder of topics listed in Table 28 and Figure 74 were of no direct interest in a more detailed examination.

Introduction of electrical vehicle propulsion necessitated a re-examination of torque distributions on the driving wheels. Much useful, though not entirely novel, work in this area was reported by Slivinskii and Titov (1970). Their interest centered on torque-dispensing in a soft terrain, where individual wheels encountered different resistance and adhesion.

Optimization of drive conditions on a curvilinear path was discussed by Boklay (1970) of ONIS-NATI. More on computerized techniques for an analysis of vehicle vibrations, this time with reference to pneumatic suspension, was published by Ignatenko and Klochkov (1970). Their brief analysis based on an auto-correlation function presents data on Russian computers and on-road input.

Torque distribution among wheels driving on soft soil was again the subject of a study by Smirnov and Lelikov (1970). The study was limited to a 4x4 vehicle and included a variety of terrain surfaces.

A tutorial paper on a driver-vehicle system was presented by Konev (1970). It consisted, however, of abstracting the works by Rashevsky (1959-1964) of the University of Chicago. Such belated availability of this American work to the Russian student shows the time lag in the discussed area. But Rashevsky's work is practically unknown among American automotive engineers (see Bekker 1956).

Amid this variety of mathematical modelling of the system and input data collecting, it was rather surprising to discover the familiar name of Ageikin (1970), who after all these years of pioneering and prolific work on soil-vehicle relationship deemed it necessary to return to the problem of soil value system.

He was right in noticing that the existing load-penetration functions as discussed in Chapter II apply only to homogeneous soils. However, by quoting only reference

(Bekker, 1960) he did not realize the potential of bevameter testing technique that was extended over stratified soils, most recently reported by Bekker (1969).

Ageikin proposed his own method. It is elegant, pragmatic, and simple. How good it is remains to be seen in practical applications. If a soft soil layer of depth h (Figure 76) is considered, then the relationship between ground pressure p and sinkage z may be expressed by equation:

$$p = 1/\left[\frac{2}{\pi p_s} \tan^{-1}\left(\frac{h-z}{aD}\right) + \frac{aD}{Ez} \tan^{-1}\left(\frac{h-z}{aD}\right)\right] \tag{358}$$

where p_s is a "bearing capacity" of soil defined two decades ago by N. N. Ivanov (1950) as:

$$p_s = E\,(0.0125 \text{ to } 0.003) \tag{359}$$

Here E is modulus of elasticity; a is a coefficient characterizing the decrease of stresses in ground depth; and D is the diameter of the loading area equivalent to the area of the test instrument.

The reliability of equation (358) is not known. But the significance of the emergence of a more universal soil value solution, as late as 1970, cannot be overlooked.

Another issue of the Automobilnaya Promyshlennost was devoted again to the optimization of a man-vehicle system. The Moscow Automobile Institute (Ostrovtsev and Derbaremdiker, 1970) apparently has been conducting extensive studies on man's sensitivity to vibrations. Useful data produced criteria and a number of semi-empirical solutions based on experimental work.

Various examples of computerization of problems related to automotive engineering were discussed in publication No 9 of the Automobilnaya Promyshlennost. A contributory work by Telegin (1970) of Ust'-kamenogorskii Highway Institute on the evaluation of steerability of a motor vehicle also was reported. In a similar vein, Zhukov (1970) of Belorussian Institute of Technology reported a mathematical analysis of interrelation between elements of an articulated vehicle affected by road roughness – a fine, although not too comprehensive, approach to the problem, with three degrees of freedom.

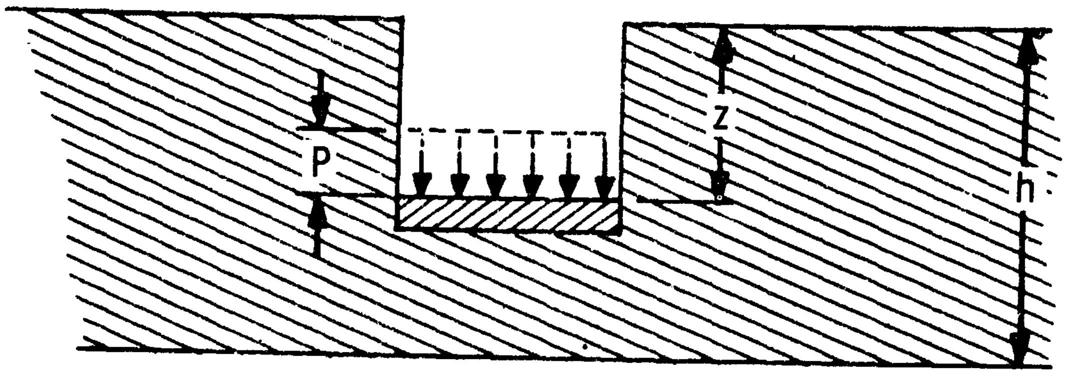

Figure 76 Ageikin's 1970 Scheme for Penetration of Soft Soil Overlaying a Hard Pan.

Statistical analysis of vehicle mobility on terrain characterized by random distribution of soil parameters was undertaken by Bezborodova (1970). This fine work provides input data, as well as principles of their analysis. The databank on transmission loads of wheeled and tracked tractors was fraught with statistical information by Skundin and Dobrokhlebov (1970) of NATI.

Application of generalized harmonic analysis to a study of tractor stability and vibrations was continued by Popov et al. (1970) under the auspices of NATI. This tutorial paper was concerned with the method rather than the results. Another methodological study was published by Prikhodko and Shchupak (1970) of NATI, in respect to analyzing the elements of external resistance forces acting upon tractors.

Since the "most useful tools in the evaluation of optimum parameters of new tractors are the results of statistical analysis of performance of analogue machines, "Korsun and Levitanus (1970) of HTE* produced an interesting paper as to how to perform such a task.

More attempts at computerization in the assessment of traction of motor vehicles in general, and tractors in particular, were illustrated in the work by Lysov (1970) of NATI. This included electronic schemes and comparison between computed and experimental values. In the same vein, Fomin et al. (1970) of the Odessa Institute of Marine Engineers discussed mathematical solutions for optimization of fuel injection in diesel engines.

The Tractor and Agricultural Machine Magazine closes the 1970 volume with a system analysis of the automation of tractor work (Shipilevskii, 1970, NATI). This perhaps

* Acronym not identified.

illustrates best the gradual progression from parametric analyses to system analysis and automation.

The brief review of 1970 literature brought only the chronological highlights of material analyzed, because it would be impossible to mention all the articles and themes which served the purpose of assembling Table 28 and Figures 74 and 75.

It is intended, however, that this section together with the preceding ones clearly show that

- a systematic terrain-vehicle system analysis based on mathematical models and sound engineering practice is the next thing to come in Russia.

The Russian engineers say so. Kocheulov and Korsak (1970) of NATI, after their unusually detailed review of an American book on terrain vehicle systems analysis (Bekker, 1969), concluded that, "It is most desirable to translate it into the Russian language."*

As shown before, thus far we have been leading in many aspects of the discussed field of endeavor. Now, the question arises, for how long? The answer to this question may not be satisfactory if it is realized that American research work has not been entrusted to automotive and tractor engineers, such as those representing the Russian NAMI, NATI, and IMESH. Instead, in the haste and emergency of World War II it was placed under the control of civil engineers and environmental scientists, because it was erroneously assumed that the soil, the climate, and the geology are "the problem." As Table 28 and the review of Russian work show,

- the soil and other problems are minimal if compared to other problems of automotive engineering nature.

Thus the revitalization of the American effort in terrain-vehicle system evaluation depends on:

- managerial decisions and radical reorganization of the "status quo" prevailing since World War II.

* The book is scheduled to appear in Russian translation in 1972.

CHAPTER VII

Epilogue

Postscripts

The availability of Russian literature in the U.S. often fluctuates beyond prediction. Libraries do not receive the subscribed material regularly, bookstores are not responsible for delays or "our of print" orders, and individual attempts to obtain a publication may be a bonanza, or a fiasco. Thus, it is difficult to perform a study based on currently published material, without continuously adding delayed information and/or rewriting the original text because of a new addendum, which in itself is prone to errors and omissions.

This volume, although based primarily on an existing, readily available collection of data, was affected by the same problem. The most characteristic information that was received after the completion of the main chapters had to be incorporated in the already finished text with all the necessary changes to the original; other data which did not affect the main theme and conclusions, however, were relegated to the postscripts, and left there to give only additional testimony to the principal thesis of this work. This solution hopefully eliminated uncomfortable footnotes and confusing paranthetic amplifications, thus presenting a clearer picture of the Russian striving to the optimization of terrain-vehicle systems. The additional references also further exemplify the most recent important contributions to the locomotion mechanics and soil-machine systems analysis.

Attempts to make soil a fully measurable material obviously have not relented, although the search was mainly oriented toward a definition of such soil values which could be used in empirical and semi-mathematical solutions of ploughing, tilling, scraping, and bulldozing. For locomotion purposes, little had been added when Turetskii (1969) wrote on various soil states versus coefficients of friction and Savinykh (1969) renewed efforts to treat the ground according to the Maxwell relaxation model, while Matsepuro (1969) wrote about agricultural produce and materials as visco-plastic bodies. Characteristically, soils were not included in this study.

This gap was filled with a paper by N^vichikhin (1968), and primarily with the excellent compendium by Razorenov (1968) on ground probing by means of penetrometers. Although locomotion again was not the objective of this work, the comprehensive and highly professional treatment of the problem further illustrates the seriousness of Russian engineers in a search for better soil-value systems. Razorenov's book clearly shows that each branch of soil-machine technology – hence, also off-road locomotion– needs different ground measurements. His work, however, does not seem to have progressed beyond the stage described before, although the awareness of the problem was greater. This is exemplified in the clasic by Sedov (1970). Concerned with continuum mechanics, his book was written on the highest professional level, comparable to similar work in the Western World. However, direct applications to, or practical use of, this type of mechanics in the study of the soil-vehicle interface still remains to be seen.

Much practical advancement appears to have been made in road building machinery and vehicles. Klazhinskii et al. (1967) wrote on automatization and automation equipment, but not on soils. However, Krivishin et al. (1969) reviewed work by Zelenin (1968) and other authors previously quoted in this volume, who still rely to a large extent on the DORNII impact penetrometer for evaluation of soil cutting and scraping. Apparently, Russian civil engineers have decided to follow their own method of measuring soil properties. These empirics did not prevent Alekseev from starting to work much earlier (1964) on optimization of design parameters of earth movers, and using advanced techniques (PSD functions) with computers for evaluation of loading processes of the equipment. Gurkov et al. (1962) and Artemev (1963) preceded this work with a book on theory and design, which as always predominated; Dombrovskii (1969), also using the DORNII penetrometer, specialized in excavators. Rumyantsev (1969) followed suit. An excellent book by Skotnikov et al. (1969), however, relied on Korchunov and Bernstein-Letoshnev soil values discussed in Chapter II. Work by Bekker (1960), and in particular his "Spaced link" track patents, were extensively discussed.

The excellent book by Balovnev (1969) was written in a similar vein, which produced a fine theory of equipment design and model testing in soil cutting. Dimensional analysis and a scale model study of scrapers were discussed in detail. References to American work by Bekker, Nuttall, Selig, and Schuring were quoted (for details see

Bekker, 1969). A broader approach, including analysis of the complete system, tractor-digger-ditch-soil, was most recently produced by Turetskii (1970) who used both the DORNII penetrometer and "soil resistance-to-digging" measured in kg/cm^2. In some respects this paper favorably compared to the earlier previously mentioned work by Wislicki (1969), who worked on a tractor-scraper-soil system, using Land Locomotion Laboratory's soil-value system.

In general, the road-building-machinery students found themselves in a rather "static" position because their tasks grew quantitatively rather than qualitatively. Sevrov et al. (1970) and, much earlier, Ul'yanov (1962) were interested primarily in the output, size, and design, although Ul'yanov dwelt on tire testing in soil bins, and used a dynamometer very much similar to that described in Chapter III (TsNIIMESH). He referred to work by Birulya (1949). Most of the discussed authors were concerned with mechanical systems involved. The DORNII penetrometer has been favored in earth works.

In a different vein, a number of authors wrote about tractors, carriers, and equipment used in forest technology. Gorbachevskii et al. (1969) and Zaichik et al. (1967) used only primitive concepts of motion resistance, and relied on Omelyanov's (1948) solution for pneumatic tires. Their books, however, were of a rather popular character, and were mainly devoted to operational problems of equipment; the authors are not students of soil-vehicle mechanics. Similarly the work by Kochegarov (1970) was concerned more with processes and equipment than with the environment. However, Gorbachevskii (1970) thoroughly investigated tires for forest roads. He used Berstein-Letoshnev soil values and tried to expand the formula for sinkage z at repetitive loads using equation: $z_N = \alpha + \beta \log N$, where α and β were "soil parameters" and N the number of passes. Gorbachevskii also used Culombian soil values c and φ: $\tau = c + p\tan\varphi$ and quoted Bekker's (1956) Theory of Land Locomotion.

The conclusion related to road-building-machinery students seems to apply also to the engineers in forest technology: they were not primarily concerned with soil-vehicle interface, and used information produced by agricultural and automotive engineers. Nevertheless, the fact that their problems were growing, at least quantitatively, forced them to to into the generalizations that approach system analyses.

Obviously, in this endeavor the lack of more universal soil values was still an obstacle. The previously mentioned work by Wislicki (1969) appears to be the first attempt of breaking this barrier and including the soil in the system in quantitative, physically meaningful terms. The trend to the automation of the soil-machine-vehicle complex (Kodenko and Lebedev, 1969) has undoubtedly accelerated these attempts.

Mathematical modeling of vehicles and their performance in conformity with vehicle mechanics thus again became an important issue. As if to further gather the input for terrain-locomotion system analysis, the Russian automotive engineers did not relent in building mathematical vehicle models. Among more significant recent works in this area is the book by Zakin (1967), an excellent example of applied mechanics in automotive engineering. It adds much to the earlier work by Badalov (1963) – full of parametic analyses and nomograms. Melnikov (1969), in a study of speed and drawbar pull of a tracked tractor, even included Katsygin (1962, 1964a) soil values, and quoted Bekker (1956). As design problems staggered, Skundin (1969) produced a fine textbook on transmissions, and Khachatryan (1965) dealt with statics, kinematics, and navigation of a tractor on a heavily sloped and rugged terrain. Optimization of inflation pressure speed, and torque vs soil measured in Bernstein-Letoshnev values were the subjects of work by Kochetkov (1968). Professor Opeiko (1970) embarked upon the already well covered topic of steering tracked vehicles, and developed complex equations of quasi-static turn. Advanced application of the PSD function to vehicle dynamics was published by Antyshev (1968). These are but a few selected examples of further refinement of mathematical models required in system approach, that were made available most recently.

The optimization of a soil-machine-vehicle system, and of the respective operations, was approached in the last two or three years either directly or indirectly in a growing number of books and papers. Systems analysis and operational research attracted the attention of such prominent workers as Lurie (1963) some time ago. He was probably one of the first who was concerned with statistical properties of the tractor-machine-soil complex. Optimization of tractor parameters (Kuzmenko, 1963) also was performed before Guskov's work (1966); and the selection of tractor mixes, based on mathematical analysis, was discussed by Badalov (1964) before Nagorskii (1967) published his fine work on computerization of statistical processes. Zhilin (1967) analyzed the cost-effectiveness of tractor-trailer transporation, and Vasilenko (1967, 1968a) discussed the stockastic and other processes while Gugushvilli (1968)

wrote about the variance analysis in application to agricultural machinery. Operations research in planning optima in agricultural transport was discussed by Zavalishin (1968), and similar work in value assessment of agricultural operations, by Saakyan (1968). Dmitriev et al. (1969) dwelt on modelling of energy involved in tractor-machine aggregates. Baranskii (1969) worked on a parametric evaluation of fuel economy vs effectiveness of tractors, and produced fine nomograms. Nagorskii and Bokhan (1969) presented a paper on mathematical modelling and electronic processing of system analysis in automated control of a cultivator. Lvov (1969) introduced dimensionless parameters for evaluation of tractor-machine "mobility", which appear to have been influenced by a theoretical study of increasing the speed of such a system by Andtusenko (1967).

A neat tutorial exposition of modern mathematical methodology applicable to "agricultural mechanics" was presented by Vasilenko (1968). He followed this fine work with an outline of optimization methods, which included statistics of extreme, variation calculus, linear and dynamic programmng, and technological forecasting. Similar work with specific references to the stability of operations involving agricultural machinery was tackled by Gudkov (1968). Zavalishin (1968) was concerned with optimization criteria of process effectiveness in a typical OR approach that was followed by Skryabin (1968). The latter included the PERT method, besides general principles of process programming.

The trend to operations and system analysis was interwoven with an attempt to foster computer programming, mainly for evaluation of statistical processes. Thus, Antyshev (1968) and Agasyan and Aleksandryan (1969) wrote on vehicle and machine vibrations, using a generalized harmonic analysis and electronic computational schemes. The latter also were developed by Markaryan and Khoetsyan (1969) for very specific purposes of transport of forage. Lurie and Nagorski (1969) used a similar method, considering dynamics of a two-dimensional case of agricultural tractor-machine aggregate, and presented electronic schemes for computation of the stability of such a system. Lurie even (1969) went further and considered PSD functions of soil resistance when ploughing. Sergeev et al. (1970) developed a mathematical model for optimization of soil-machine-tractor aggregates, using the lagrange multiplier. This work dovetails neatly with a similar evaluation by Guskov (1968), which appears to have originated earlier with Matsepuro ("Voprosy"... 1964).

All these "postscripts" thus confirm the thesis expounded in this volume : mathematical modelling collecting inputs and outlining the method point to the growing use of computerized techniques for optimization of design and performance with a complete terrain-vehicle-machine system. The abundance of nomograms again demonstrates that the lack of computers is perhaps the main obstacle. These "postscripts" also show the intensification of a search for soil-values by civil and agricultural engineers. Moreover, there also is a message conveyed to the effect that:

- each type of soil-machine interaction requires different, though perhaps overlapping, soil measurements.

This conclusion is contrary to an American experience whereby the civil engineers of Waterways Experiment Station insist that the "cone index" method introduced some thirty years ago for evaluation of the fill in dam construction will help (with inconsequential modifications) automotive engineers in evaluation of terrain-vehicle systems in the seventies.

The reviewed Russian literature shows that the use of a cone penetrometer is still attempted in the assessment of tillage, ploughing, and other agricultural processes, and to a certain extent, in civil engineering; but not in the automotive engineering, for evaluation of performances and design parameters of soil-vehicle system. Russian automotive literature has always been mute on this subject.

Summation

The preceding pages of this volume dealt with the development of the Russian approach to the evaluation of soil-machine-vehicle complex, emphasizing the vehicle. It is hoped that the technical detail reported here will help the technician to reorient his own road to progress. For the general readers who do not necessarily need to consider technicalities of automotive engineering in order to envision a road toward more economic and more efficient terrain-vehicle systems, the following summation, it is hoped, may be useful.

The intellectual and research climate in Russia is favorable, perhaps more than is required to balance research with development. This situation prevented excessive, crude empiricism on one hand, but did not lead to oversophisticated academic generalizations, on the other. A balanced theoretical, experimental approach, moderated by a pragmatic treatment of problems involved, seems to have provided

a mid-road between the American * and German** approaches. The favorable climate has has attracted workers of a very high professional caliber and the support of prestigious institutions; it has produced unsurpassed numbers of good publications. Innumerable R&D Institutes appear to cope with the problems in accordance with their geographic locations. They provide individual and cumulative intellectual leadership, which seems to be the only effective antidote to the inertia in their bureaucracy and in the enormity of the system.

Russian work on soil-machine-vehicle interface started approximately 35 to 40 years ago. American work, based on a similar theoretical basis, did not start until some 20 years ago. The origin of both activities may be traced to eighteenth century work in France, and to the pioneering research in Germany by Bernstein (1913). Letoshnev (1936) adapted and further developed Bernstein's semi-empirical theory based on a dimensionally defined soil-value system. Full information on this subject was not available in English until 20 years later (Bekker 1956), which may explain our late entry in this field.

The Russians have been aware of the deficiencies of the Bernstein-Letoshnev soil-value system and tried to improve it in a variety of ways (Pigulevskii, 1936; Vernikov, 1940; Troitskaya, 1947; Korchunov, 1948; Omelyanov, 1948; Antonov, 1949; Saakyan 1953; Gutyar, 1955; Tsymbal, 1958; Saakyan (1959); Ageikin, 1959; Rokas, 1960; Matsepuro and Guskov, 1961; Katsygin, 1964; Strokov, 1964; Rokas 1965; Melrikov, 1966; Guskov, 1966; Volskii, 1967; Ageikin, 1970). Finally the designer revolted against empirical "indices", which led to the establishing of a rational school of thought by NAMI and the "Minsk School," to name the few. In the meantime, American research has been polarized with an arbitrary, empirical soil-value system referred to as the "cone index" technique, which was introduced during World War II. The evolution of the Russian soil value system has not yet been completed, although the era of consolidation of the existing "know how" for locomotion purposes is clearly in sight.

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* Scientifically oversophisticated or highly crude and empirical

** Highly theoretical

The automotive and agricultural tractor engineers rely now on Bernstein-Letoshnev (1913-1936) and Katsygin (1964) soil-value systems, which are based on soil penetration tests, and on fitting the penetration curve with an exponential and, preferably, hyperbolic tangent function. The shear test curve has been fitted also with a trigonometric hyperbolic function. This procedure is in essence identical to the processing of the soil value system called the "Bevameter-values", developed by the Land Locomotion Laboratory in Detroit (Bekker, 1960). The latter differs only in form from the Russian procedure, since it uses an exponential function for fitting the penetration curve, and the modified Coulombian function for fitting the shear test data.

Penetration test curves in stratified soils are fitted by Russian engineers with the soil-value equation proposed by Korchunov (1948) and based on American work by Housel (1929). This operation bears much similarity to the process of soil-value definition proposed much later for stratified ground by Bekker (1969) and based on work by Meyerhof (1960-1961).

The Land Locomotion Laboratory soil values were developed independently in Detroit as an evolutionary transformation of the Bernstein-Letoshnev values, based on a concept originated at MIT (Taylor, 1948); as mentioned before, they also included Coulombian measures of soil strength. These values were generalized and integrated by the Land Locomotion Laboratory (Bekker 1956, 1960, 1969), in a complete technological framework, which laid the foundation for a new development acclaimed as a new discipline by a number of foreign and domestic critics. The new developments in the mechanics of land locomotion and system analysis became a methodological tool for terrain-vehicle evaluation by NASA and the aerospace industries (Bekker 1969). They spirited the development of articulated and large-wheel vehicles, some of which are in production.

These American activities attracted much attention in the U.S.S.R. The numerous references, quotations, discussions, praise, criticism, and translations of work published by the Land Locomotion Laboratory, shown in this volume, speak for themselves.

Although the Russian researchers built and tried at least 22 different types of soil-measuring devices, they did not use the "cone" for vehicle-mobility evaluation; for other cases they modified the cone penetrometer with a great sophistication.

At this time the following instrumentation is mentioned most frequently in Russian literature: penetrometer DORNII (in civil engineering), penetrometers Revyakin, ASHN-BSSR and "Minsk", and DSSH and TsIIMESH apparatuses (in automotive and agricultural tractor engineering).

The arbitrary soil indices and pertinent instrumentation have not been contemplated for use in locomotion evaluation, though they still try to find a place in tillage, ploughing, plant growing, etc.

The latest trends and indications are that a development of a "universal" soil-value system, conceptually similar to the American bevameter values, is under study (Guskov, 1969).

The soil measuring device operated on the moon, the "Lunokhod", is equipped with a cone-cum-vanes penetrometer, apparently for testing "geological" structure of moon soil, and with the "ninth" wheel plus torque-slip measuring instrumentation similar to the TsIIMESH apparatus, which provides data for vehicle designer.

Russian mathematical modelling of the soil-wheel interface does not display the variety of sophistication developed in America, though it cannot be considered inferior. As a matter of fact, the simplistic semi-empirical solutions by Bernstein-Letoshnev (1936), Vernikov (1940), Kragelski (1948), Gutyar (1955), Andreyev (1956), and many others, have methodologically as much merit as the most modern attempts based on more "rigorous" assumptions.

This fact was recognized in the early activities by the Land Locomotion Laboratory in Detroit, which opposed, prior to early nineteen sixties, the involved theories based on totally computerized input-output.

Russian mathematical wheel modelling followed a similar line, as may be deduced from the frequent references to work by Land Locomotion Laboratory.

In general, there is much continuity in Russian mathematical modelling. The Minsk School, in particular, showed great consistency in the development of soil-wheel interface models (Babkov, Birulya, and Sidenko, 1959; Matsepuro, and Katsygin, 1961; Guskov and Kuzmenko, 1964; Guskov 1964, 1966; Krasilnikov, 1966), although from time to time, individual researchers impressed the engineers with more scientific but no more accurate solutions (Glagolev and Poletayev, 1967). Russian references to Bekker (1956, 1960) and Söhne (1958) indicate that the U.S. and German work were methodologically on the same platform.*

Semi-empirical mathematical modelling of pneumatic tires was impressive. It was Omelyanov (1948) who seems to have pioneered the first primitive tire theory; his was a "great leap" in comparison to the empirics by McKibben et al. (1940) in the United States. Briukhovets (1957) also ran laboratory and field tire tests which produced standard procedures GOST 7057-54, while the similar Amercian tests performed later (Powell and Green, 1965) have had intangible practical meaning. They still represent an enormous collection of unused data.

Such a research policy was seldom espoused by the pragmatic Russians. Thus, Ageikin (1959) established a semi-empirical tire theory based on existing "know how" and facts. At the same time, the Land Locomotion Laboratory in Detroit independently established an almost identical theory (Bekker 1960). The coincidence, not only in methodology but also in the main assumptions and some aspects of the solution, showed again the common school of thought and the same professional niveau, prevailing in both countries**

While one group of Russian researchers worked on a theory, the other provided field test data in order to enable one to test the theory (Semenov and Armaderov, 1961; Armaderov and Semenov, 1962; Bocharov, 1961; Siliukov, 1962, etc.).

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* The work performed in England, particularly by Reece (1965), also belongs to the same school of thought.

** Similar methodological trend already existed in Germany (Soehne 1956).

The formal translation into Russian of Bekker's (1956) book on Theory of Land Locomotion and of the series of articles published by Machine Design (1959-1960) seem to mark the entry of Land Locomotion Laboratory's work into the Russian "research market", which was booming with all kinds of activities. The Research Institutes and schools such as NAMI and MVTU, for instance, performed more tests and tire evaluations than tests known to this writer, in Vicksburg and Detroit. In addition, new ideas and new theories came and went, but not without some interesting afterthoughts by (Strokov, 1964). The Minsk School (Matsepuro, Katsygin, Guskov, 1966) also did not remain dormant, and further developed a semi-empirical tire theory based on acknowledged cooperation with NAMI and VIM, and under less explicitly acknowledged influence of the U.S. work performed in Detroit. At the same time in Poland Soltynski (1966) and Wislicki (1969) adopted the Land Locomotion Laboratory's soil-value system, which also was analyzed and reported in the text books in Hungary (Sitkei, 1967) and Tchekhoslovakya (Grechenko, 1967).

Research on tracked vehicles started long before tire research (Zaslavski, 1932; Kristi, 1937) and was unique in its mathematical generalization of performance-design parameters. The publication of Canadian-American work, (Bekker, 1950, 1955, 1956) had strong repercussions which can be seen even in the same approach to the solutions of track-soil interface (Matsepuro and Guskov, 1961). The overly theoretical work (Opeiko 1961) found cool reception.

The Russian track-soil research led to a novel practical concept based on two types of soil values: Bernstein-Letoshnev-Katsygin type for inorganic soils (turf, peatmoss, etc.). Incidentally, Housel expounded his ideas at the University of Michigan in 1929. But American research work, which dramatically slowed down after 1960-61, did not catch catch up with organic and non-homogeneous soils until almost 30 years after Housel and 10 years after Matsepuso and Guskov (Bekker, 1969).

Guskov's (1964) approach to track design and performance evaluation provided solutions only partially matched by a similar work in England (Reece 1965) and by rather limited attempts in this country (Bekker 1969).

In general, however, the U.S.S.R., U.S., and U.K. thinking in this area is the same*, and the differences encompass the form rather than content; what is more significant, they imply the existence of a more serious and intensive work in Russia than elsewhere. The strength of this work lies in the publication of excellent textbooks (Ul'yanov, 1962; Ul'yanov, 1964; Khachatryan, 1964, Zaichik et al., 1967; Vasiliev et al., 1969; Fedorov, 1969; Razorenov, 1968; Bakhtin, 1969; Saakyan, 1969; Skotnikov, 1969; Revuta, 1969; Gorbachevskii, 1969; Skundin, 1969; Ostrovtsev, 1969; Ul'yanov, 1969; Sevrov, 1970).

Russian work, however, was not free from overlapping, lack of communication, or human frailty (Klochkov, 1967). Improvements of track, wheel, and vehicle theories were attempted, not necessarily through the revision and amelioration of original assumption, but often by unscrupulous addition of more assumptions to the old ones. This course of action, however, appears as much inevitable in Russia as it is elsewhere.

But such misguided ventures do not seem to be as expensive in Russia, because they were mainly based on paper and sliderule work, as opposed to similar attempts in this country, where little is done without the expensive computer and other push-button equipment.

Dimensional analysis, which has heavily preoccupied one segment of researchers in this country, seems to be practically nonexistent in Russia locomotion research. A new trend, however, appears to indicate some revision of this attitude (Guskov, 1969) along the lines sketched by Bekker (1969).

The problems of vehicle dynamic response to random terrain surface roughness has been gaining momentum steadily, undoubtedly under the influence of American work, though Russian researchers seldom refer to it, if at all (Parkhilovskii, 1961; Parkhilovskii and Zaitseva, 1964; Rotenberg, 1965; Lurie, 1969).

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* The German, Polish, Hungarian and Czechoslovakian agricultural research belongs to the same school.

As if realizing the crudeness of approximations attainable by these methods, a number of researchers proceeded with less expensive, and perhaps no less accurate, solutions (Birulya, 1949; Torchinskii, 1962). Russian automotive engineers appear to have favored this more simple approach. Nevertheless the mathematical modelling of the dynamic vehicle system is fast advancing. The lack of computers is the only obstacle to progress.

As a whole, the Russian mathematical modelling of vehicle-machine-soil interface represents a continuous evolutionary process, which unveils gradually broader solutions within the confines of the same school of thought. Pragmatism and continuity appear to be strong ingredients of the process.

The process is marked by increasing attempts of parametric evaluations of design performance and cost which grew from relatively simple schemes (Letoshnev, 1963; Goriachkin, 1937; Gruzdev, 1944; Chudakov, 1962) to more complex ones (Katsygin, 1964; Guskov, 1966; Vasiliev et al. 1969; Kleinin, 1970, etc.). These, in turn, gradually started showing all the features of what is called today the Systems Analysis (Guskov, 1968, etc.).

The development of the latter, though not yet formalized, is seen in an increasing number of computerized soil-machine-vehicle models and tutorial mathematical papers concerned with statistical processes, optimization, operations research, technological forecasting, etc. (Pevzner, 1964; Khacnatryan, 1965; Degtyarenko, 1966; Zakin 1967' Nagorski 1967' Ahlin, 1967' Vasilenko, 1968; Gugushvilli, 1968; Zavalishin, 1968; Skraybin, 1968; Baranski, 1969; Melnikov, 1969; Nagorski and Bokhan, 1969; Sergeev et al., 1970, etc., etc.).

The objective of these studies is not necessarily the inventing of novel modes of locomotion, but the improvement of effectiveness and reduction of cost of the conventional ones. Savings of natural resources and the economy of the system is also stressed from the rational viewpoint. The obstacles to progress appear to be the lack of managerial techniques, comparable to those developed in the U.S., and the lack of computers. These obstacles, according to the best sources, are being overcome (Kozlowski 1969; Nikitin, 1967, etc.) and the work in accumulation of databanks as well as the continuing improvement of mathematical models goes at full speed, as illustrated by the references.

Thus the Russian research is gathering inputs and developing the "software" while waiting for computer "hardware". Paradoxically, the situation is the reverse in this country. The U.S. has ample electronics of superb quality that is waiting for better, more practical mathematical models of soil-vehicle interface, better environment and mission input, and a clearer quantitative operational requirement. But we do too little work on that kind of "software"; in spite of the lack of basic ingredients required for systems analysis, we too often spend effort and money on vast computerized programs with very little practical engineering input.

The decline of our national and international leadership in science of off-road locomotion and ground mobility started in the early sixties. If this decline continues, the Russian R&D in Terrain-Vehicle Systems, which already is quantitatively and qualitatively superior, will soon produce more economical and more versatile vehicles that will be better adapted to the environment and to the mission requirements than any vehicles produced by lengthy trial and error, or by misguided expensive and sophisticated analyses.

Comparison of the contents and the numbers of themes published in 1970 by the leading Russian and American professional magazines leaves little doubt as to where the leadership may go - if it has not already gone. A comparison also shows that the problems are primarily of an automotive-engineering nature. The question of soil-vehicle relationship, though all important in system analysis, reflects only one of many aspects of research and development of motor vehicles.

This was the reason why the Russian efforts concentrate at NAMI, MAMI, and at those institutes which are partially responsible for motor vehicle R&D (TsNIMESH, VISKHOM, VIM, etc). The civil engineering R&D Institutes (MADI, KADI, etc.) look after their highly specialized problems, with a rather fleeting attention to the very special soil-vehicle problems, such as operating bulldozers, canal diggers, and the like (Fedorov, 1969; Skotnikov, 1969, etc.).

This is in contrast with the role assigned in this country, during World War II, to the civil engineering and environmental institutions in shaping the philosophy and conducting research in automotive ground mobility.

Conclusions

Much may be deduced from someone's failure to achieve a goal or from the difficulty in its attainment. It is hoped that the present work described the problems faced in Russia with a sufficient clarity so that the lesson may be learned, and that it may be unnecessary to dwell, in the conclusions, on imperfections of Russian research, again. However, the underscoring of Russian success may be worthwhile because the learning from success is more positive, direct, and constructive than learning from a failure. The material reviewed in this work displays the fast emerging leadership and superiority of Russian research in off-road locomotion. It also shows, hopefully, that the cause of such advancement where others stand still or fall behind, must be ascribed to:

- favorable research climate
- balance between theory and empirics
- highly qualified personnel and high level institutional support
- austere, sober, pragmatic, professional planning
- search for economy and effectivenes, rather than for spectacular "breakthroughs" and "instant" solutions
- reliance on intellect rather than on machines of undue sophistry
- publication of books and top notch professional papers
- recognition that the problem is of automotive nature and that the assignment of mission responsibility and leadership must go to the appropriate organization, with other professions serving in an ancillary capacity.
- emerging of a methodological uniformity and school of thought which is leading to a systems approach in the very modern tradition of locomotion engineering.

The public, the industry , and many of those responsible for progress in this country appear to be unaware of the pragmatic and continuous work going on in Russia in such unglamorous and unattractive field as off-road locomotion and ground mobility. The present work has hopefully revealed at least the headlines. And it is time we realize that much must be changed before we regain our leadership in the area we once pioneered.

May 25, 1971

BIBLIOGRAPHY

A

Afanas'yev, V. L. and **Khachaturov**, A. A. (1966) "Staticheskie kharakteristiki mikroprofilya avtomobilnykh dorog i kolebanii avtomobilya" (Statistical characteristics of road microprofile and vehicle vibrations) Avtom. Prom. No. 2

Agasyan A. V. and **Aleksandryan** K. V. (1969) "Vzaimodeistvie navesnykh i pritsepnykh mashin s traktorom" (Interaction between the suspended and towed machines, and the tractor) "Trudy" Arm NIIMESH vol. VII Erevan

Ageikin, Ya S. (1959) "Opredelenie deformatsii i parametrov kontakta shiny s myagkim gruntom" (Determination of ground contact parameters in soft ground) Avtom. Prom. No. 5

Ageikin, Ya. S. (1959) "Issledovanie roboty shin peremennogo davleniya na deformiruemom grunte" (Study of pneumatic tires with variable pressure, on soft ground) Publ. by Acad. of Sc., SSSR, Moscow (quoted from Shavlov, 1963)

Ageikin, Ya. S. (1960) "Vybor razmerov shin s reguliruemym vnutrennim davleniem vozduha" (Selection of tire dimensions with the regulation of inflation pressure) Avtom. Prom. No. 12

Ageikin, Ya. S. (1970) "Otsenka deformiruemosti grunta pri rassmotrenii prokhodimosti avtomobilei" (Evaluation of ground deformation for automotive mobility") Avtom. Prom. No. 6

AIA. (1962) "8th Aerospace Technical Forecast, 1962-1972" Aerospace Industries Assoc. of America, Washington, D. C.

Akhmedov, A. I. (1963) "Analiz tyagovykh kachestv avtomobilya s pomoshch'yu elektronno-tsifrovykh vychislennykh mashin" (Analysis of traction of an automobile by means of a computer) Avtom. Prom. No. 9

Aksenov, P. V. and Polyakov, A. S. (1968) "Analiz skhem silovoi peredachi avtomobilei vysokoi prokhodimosti" (Analysis of power train subsystems of high mobility motor vehicles) Avtom. Prom. No. 11

Alekseev G. W. (1964) "Mashiny dla zemlyanykh robot" (Machines for earthworks) Mashgiz, Moscow

Amplevskaya (1955) "Specific Soil Resistance and Methods for its Determination" Trudy (Soyuznikha), Tashkent. English Translation NTML, Auburn, Ala

Andreev, A. A. (1953) "Analiticheskaya razrabotka nyekotorhkh voprosov kinematiki koles. . . " (Analytical study of some problems of wheel kinematics. . .). Sbor. trud. zemled. mech. Vol. II. Selhozgiz. Quoted from Andreev (1956)

A

Andreev, A. A. (1956) — "Kinematics of Rolling a Rigid Wheel in a Rut" Sbor. trud. zemled. mech. Vsescyuz. Lenin Akad. Sekhoz. Nauk, Vol 3 (English translation by NIAE).

Andrusenko, P. M. (1967) — "Teoreticheskie osnovy povyshenya rabochikh skorosti traktornykh agregatov" (Theoretical principles of increasing the working speeds of tractor aggregates) Zemledelcheskaya Mekhanika Vol. VII, Moscow

Antonov, A. S. (1949) — "Teoria gusenichnogo dvizhitela" (Theory of a tracked prime mover) Mashgiz, Moscow

Antonov, D. A. (1961) — "Metod postroeniya diagrammy ustoichivosti mnogoosnykh avtomobilei" (Method of determining a diagram of stability of multi-axle automobiles) Avtom. Prom. No. 11

Antonov, D. A. (1962) — "Ob otsenke ustoichivosti krugovogo dvigheniya mnogoosnykh avtomobilei. . . " (Assessment of stability of multi-axle vehicles, in a turn) Avtom. Prom. No [illegible]

Antonov, D. A. (1963) — "K raschetu proektiruemykh avtomobilei na ustoichivost dvizheniya" (Design stage evaluation of automobile drive stability) Avtom. Prom. No. 9

Antonov, D. A. (1968) — "K voprosu o korektsii koeffitsienta soprotivlenya ukhodu elastichnogo kolesa" (Correction of the coefficient of cornering for an elastic wheel) Avtom. Prom. No. 12

Armaderov, R. G. et al. (1964) — "Rabochie kachestva avtomobilei na arochnyh shinakh" (Working performance of automobiles with rolligon tires) Avtom. Prom. No. 4

Armaderov, R. G. and Semenov W. M. (1962) — "O prokhodimosti gruzovyh avtomobilei na arochnykh i standartnykh shinakh" (Mobility of trucks with rolligon' and standard tires) Avtom. Prom. No. 3

Armaderov, R. G. et al. (1965) — "K voprosu opredelenya nekotorykh fiziko-mekhanicheskikh charakteristik bolotno-torfyanykh pochv" (The problem of definition of some physico-mechanical properties of mud-turf soils) sbornik trudov nauchnoi konferentsii, First Ed., Minsk 1959

Armashov, Ju W. and Zheglov, L. F. (1968) — "K voprosu kolebanii odnoosnykh bezramnykh pritsepov" (Problem of vibrations of single axle frameless trailers) mashinostroyenie No. 12

Artemev (1963) — "Osnovy teorii kopaniya gruntov skreperami" (Theory of ground moving with scrapers) Mashgiz, Moscow

Asanov, A. I. (1962) — Report published in "Mekhanizatsia i Electrifikatsya Sel'skhogo Hozyaistva," No. 5

A

Atoyan, K. M. and Akopyan R. A. (1966) — 'K voprosu o primenenii korrelatsionnogo analiza v issledovanii nagruzochnogo rezhima nesushchei sistemy avtomobilya" (Problem of application of correlation analysis to a study of load regime of automobile suspension) Avtom. Prom. No. 8

Aviation Week and Space Technology (1970) — 'Lunokhod Resumes Lunar Travel" Dec. 21 issue

Aziyamova, I. N. (1957) — 'K voprosu opredelenya nekotorykh fiziko-mekhanicheskikh characteristik bolotno-torfyanykh pochv" (The problem of definition of some physico-mechanical properties of mud-turf soils) Sbornik trudov nauchnoi konferenstsii, First Ed., Minsk 1959

Aziyamova, I. N. (1959) — 'K voprosu nekotorykh fiziko-mekhanicheskikh kharakteristik bolotno-torfianyh pochv" (Physico-mechanical properties of mud-turf soils) Proc. Conf, Minsk quoted from "Voprosy Selskokhoziaistvennoi Mekhaniki," Minsk 1964

B

Babkov, V. F. (1956) — "O soprotivlenii dvigheniyu kolesnyh povozok po deformiruyushchemsya gruntu" (Motion resistance of wheeled vehicles in soft ground) Trudy MADI Ed. 18

Babkov, V. F. (1959) — "Prohodimost kolesnykh mashin po gruntu" (Mobility of wheeled machines in terrain) Avtotransizdat. Quoted after Guskov, 1966.

Babkov, V. F., Birulya, A. K. and Sidenko, V. M. (1959) — "Prokhodimost kolesnykh mashin po gruntu" Avtotrakizdat (quoted from Guskov and Kuzmenko, 1964)

Badalov, Ya. M. (1963) — "K voprosu opredelenya optimalnogo vesa kolesnykh agregatov" (Problem of weight optimization of wheeled aggregates) "Trudy" Vol. II, Minsk

Badalov Ya. M. (1964) — "Osnovnye voprosy agregatirovanya kolesnykh traktorov" (Principal questions of the aggregation of wheeled tractors) "Trudy" Vol. III, Minsk

Bailey, P. (1954) — "The NIAE Single Wheel Tester" NIAE Rep. No. 40

Bakhtin, P. U., et al. (1969) — "Pochvovedenie" (Guide to Soils) Akademy of Sciences, USSR, Moscow

B

Bakhtin, P. U. (1969)	"Issledovaniya fiziko-mekhanicheskikh i teknologicheskikh svoistv osnovnykh tipov pochv, SSSR" (Study of physico-mechanical and technological properties of main types of soils in the SSSR) Kolos, Moscow
Balovnev, V. I. (1969)	"Fizicheskie modelirovanie rezanya gruntov" (Physical models of ground cutting) Mashinostroyene, Moscow
Baram, E. G. (1963)	"Metodika normirovanya mekhanizirovanykh polevykh rabot" (Method of normalization of mechanized field work) GOSNITI quoted from Trudy TJNIIMESH, Vol. V.
Baranskii, A. N. (1969)	"Raschet tyagovykh i toplivykh pokazateli S-H traktorov dla razlichnykh uslovii" (Calculation of tractive and fuel-economy indices of agricultural tractor under various conditions) "Trudy" Vol. VI. Minsk
Becker, G. (1926)	"Motorschlepper" (Motor Tractors) Krayn, Berlin
Bekker, M. G. (1948)	"An Introduction to Research on Vehicle Mobility" Can. Dept. of Nat'l Def., Ottawa, Ont., 2nd & 3rd Printing APG, Aberdeen, Md., and OTAC Warren, Mich.
Bekker, M. G. (1950)	"Relationship between Soil and a Vehicle", SAE Journal, May & July Issues (also see Proceedings 1951)
Bekker, M. G. (1951)	"Trajectories of Principal Stresses under Wheel Action, traced from McKibben's experiment with Haefeli's method (unpublished)
Bekker, M. G. (1955)	"Wheels or Tracks Automobile Engineer, No. 6
Bekker, M. G. (1955 a)	"A System of Physical and Geometrical Soil Values for Determination of Vehicle Performance and Soil Trafficability" Oroc. Interserv. Symp. Stevens Institute of Tech., and Duke Univ., Office of Ord. Res., Durham, N. C.
Bekker, M. G. (1956)	"Theory of Land Locomotion" Univ. of Michigan Press, Ann Arbor, Mich. 2nd Edition, 1962
Bekker, M. G. (1957)	"Latest Developments in Off Road Locomotion" Franklin Institute Journal No. 5.
Bekker, M. G. (1958)	"Mechanics of Vehicle Mobility in Off-the-Road Locomotion", Applied Mechanics Reviews, No. 8
Bekker, M. G. (1959-1960)	"Cross Country Locomotion", Machine Design 24 Dec. 1959, 1 Jan 1960, 21 Jan. 1960 4 Feb. 1960

B

Bekker, M. G. (1960) "Off the Road Locomotion", The Univ. of Michigan Press, Ann Arbor, Mich.

Bekker, M. G. (1961) "Evaluation and Selection of Optimum Vehicle Types under Random Conditions" First Int. Conf. on Terrain-Vehicle Systems, Edizioni Minerva Tecnica, Torino

Bekker, M. G. (1963) "A Definition of Mechanical Mobility" Ground Support Equipment, Aug-Sep. Issue

Bekker, M. G. (1963a) "Crisis in Ground Mobility" Allison Symp. Indianapolis, Ind.

Bekker, M. G. (1964) "Introductory Remarks... (and) Strategy of Approach to Land Mobility" SEA 782 G, New York, N. Y.

Bekker, M. G. and Butterworth, A. V. (1965) "Terrain-Vehicle System Evaluation" Journal of Terramechanics No. 2 and SAE SP-261

Bekker, M. G. (1969) "Introduction to Terrain-Vehicle Systems", Univ. of Michigan Press, Ann Arbor, Mich.

Bekker, M. G. (1969 a) "Engineering Optimization of Terrain-Vehicle Systems" TR No. 10421 (LL 133) U. S. Army Tank Automotive Cmd., Warren, Mich.

Bekker, M. G. (1970) "Closing Remarks" TRW-ISTVS Symposium, TRW, Redondo Beach, Calif.

Belen'kii, Ju. B., et al (1968) "K voprosu o zatrate energii na kolebaniya avtomobilya" (Problem of energy loss in vehicle vibrations) Avtom. Prom. No. 9

Belskii, A. I. (1963) "Analiticheskii raschet skorostei dwizheniya avtomobilei s uchetom peremennoi velichiny koefficienta soprotivleniya kacheniyu" (Analytical evaluation of automobile speed considering variable coefficient of motion) Avtom. Prom. No. 10

Berenyi, Ivan (1970) "Computer in Eastern Europe" Scientific American Vol. 223, No. 4

Berliner, J. (1969) "When Ivan has a New Idea, What Makes Ivan Run?" Innovation, July, No. 3

Bernstein, R. (1913) "Probleme zur experimentallen Motorpflugmechanik" (Problems of experimental mechanics of motor ploughs), Der Motorwagen No. 16

B

Bezborodova, G. B. (1970) "Veroyatnaya otsenka prokhodimosti avtomobilya po statisticheskim raspredelenyam kharakteristik dorozhnykh uslovii" (Probabilistic evaluation of vehicle mobility on road conditions defined by a statistical distribution of parameters) Avtom. Prom. No. 9

Biernacki, H. (1960) "The Problem of Stability of Mounted Implements" Roczniki Nauk Rolniczych Vol. 67 Seria C No. 4. Translated into English and published for the NSF and USDA OTS 60-21569, Warsaw (1963).

Bocharov, N. F., et al (1961) "Ispytanya pnevmokatkov na snegu" (Tire tests in snow), Avtom. Prom. No. 11

Bocharov, N. F., et al (1963) "Ispytanya pnevmokakov na vesennei pakhote" (Field tests of tires in springtime) Avtom. Prom. No. 4

Bocharov, N. F., et al (1964) "Osobennosti kachenia pnevmokatkov po tverdoi doroge i deformiruemym gruntam" (Particularities of motion of pneumatic tires on hard and deformable ground) Avtom. Prom. No. 10

Boklay, V. M. (1970) "Usloviya vozmozhnosti krivolineinogo dvizheniya avtomobilya" (Conditions of a curvilinear drive of an automobile) Avtom. Prom. No. 3

Briuhovets, D. F. (1957) "Vzaimodeistve hodovoi systemy ballonnogo traktora s pochvoi" (Relationship between balloon tired tractor and the soil) Avtotrak. Prom. No. 12

Brylov, S. A. & Grabchak, L. G. (1970) "Transport pri geologorazvedochnykh rabotakh" (Transportation for geological survey) Publisher's name not available, ref. incomplete.

Bucher, E. (1948) "Beitrag zu den theoretischen Grundlagen des Lavinenbaus." (Contribution to theoretical principles of avalanche structure theory), Kummerly & Frey, Bern.

Bureau of Yards and Docks (1949) "The Physico-Mechanical Properties of Snow..." Translation Akad. Sc. USSR, Moscow

Bureau of Yards and Docks (1949) Collected papers of the Soviet Commission for airfields and roads, USSR Akad. of Sciences, Moscow.

C

Cherevan', V. N., et al (1966) "Primenenie metoda elektricheskogo modelirovaniya dla issledovaniya kolebanii traktora" (Application of electric analogues in modelling tractor vibrations) Traktory i Selkhozmashiny No. 11

Chudakov, D. A. (1962) "Osnovy teorii traktora i avtomobilya"(Principles of theory of a tractor and automobile) Selhozizdat, Moscow

Cohron, G. T. (1963) "Soil Sheargraph", Agricultural Engineering, Oct. Issue

Crandall, S., et al (1958) Random Vibrations, Mass. Inst. of Tech. Press, Cambridge, Mass.

D

Dagan, G. & Tulin, M. P. (1968) "A Study of the Steady Flow of a Rigid-Plastic Clay beneath a Driven Rigid Way" Hydronautics, Inc. Reports 923-1 prepared for Cornell Aeronautical Laboratories - ARPA, Laurel, Md.

Degtyarenko, V. N. (1966) "Postroyenie epyur skorosti i vremeni dvizheniya avtomobilya po doroge" (Tracing diagrams of speed and time for vehicle motion on the road) Avtom. Prom. No. 12

Dmitriev, A. M. et al (1969) "K voprosu energeticheskoi otsenki mashinno-traktornykh agregatov" (Energy evaluation of tractor-machine aggregates) "Trudy", Vol. VI, Minsk

Dombrovskii, N. G. (1969) "Ekskavatory" Mashinostroenye, Moscow

Dubrovski, A. A. (1955) "V P Goriachkin, Founder of Agricultural Mechanics", Transl. NTML Scientific-Technological Society for Agricultural and Forestry Management, Moscow

E

Erikson, R. (1949) "Medens friction mot sno och is" (Friction of snow and ice), Meddelande Nr 34-35 (with English summary) Stockholm

F

"Farm Mechanization in the Soviet Union" (1959) — Report of a Technical Group, USDA, U. S. Govt. Printing Office, Washington, D. C.

Fedorov, D. I. (1969) — "Mashiny dla zemlyanykh rabot" (Machines for earthworks) Izd. Transport, Moscow

Fedoseeva, K. I. (1967) — "Sozdanie otraslevoi sistemy nauchno-tekhnicheskoi informatsii Ministerstva Avtomobil'noi Promyshlennosti SSSR" (Establishing a branch system for dissemination of information of the Ministry of Automotive Industry) Avtom. Prom. No. 8

Fidelev, A. S. (1970) — "Povyshenie proizvoditelnosti stroitelnykh mashin" (Increase of productivity of construction machinery) Budivestnik, Kiev

Filatov, L. S. (1961) — "Issledovaniya tiagovykh svoistv traktora DI-54 pri zimnei ekspluatatsii ego v selskomkhozyaistve" (Study of tractor pull in winter time, in agriculture) Doctorial thesis quoted after Klochkov (1967)

Filyushkin, A. W. (1964) — "Ispytanye shin 14,00-20 razlichnoi sloinosti na deformiruemykh gruntakh" (Tests of tires with various ply numbers, on soft ground) Mashinostroyene No. 8

Filyushkin, A. V., et al (1966) — Vliyanie tipa silovogo privoda... na raskhod topliva" (Effect of transmission type upon fuel consumption) Avtom. Prom. No. 1

Fomin, Uy. Ya. et al (1970) — "Osnovy matematicheskogo resheniya zadachi opredeleniya optimalnykh parametrov toplivoi apparatury" (Principles of a mathematical solution of optimum parameters of fuel (injecting) apparatus) Trakt. i Sel'khozmash No. 10

Foster, John S., Jr. (1969) — "The Case for Defense Research and Development", Dept. of Defense, Bull, Cornell Aeronaut. Lab., Buffalo, N. Y.

Frenkin, M. S. (1962) — "Podvizhnost avtomobilei na peresechnnoi mestnosti" (Cross country automotive locomotion) Abridged translation of work by M. G. Bekker, published in Machine Design. Avtom. Prom. No. 4

G

Galtsgori, M. M., Malinovskii, I. Yu and Pasynkov, R. M. (1969)	"Stend dla issledovaniya sistemy doroga-avtopoezd-tchelovek" (Test stand for an analysis of road-vehicle-man system) Avtom. Prom. No. 6
Garbari, F. (1949)	"Resistenza al movimento dei veicoli a ruote..." (Motion resistance of wheeled vehicles), ATA Rediconti, Della II Riunione... Rome
Gastev, B. G. and Melniskoi, V. I. (1967)	"Osnovy dinamiki lesovoznogo podvizhnogo sostava" (Principles of dynamics of transport logging equipment) Lesnaya Promyshlennost, Moscow
Genbom, B. B. et al (1968)	"Obshchii analiticheskii metod opredeleniya parametrov kharakterizuyushchikh razgonnye kachestva i toplivnuyu ekonomichnost avtomobilei" (General analytical method for determing acceleration and fuel economy parameters of an automobile) Avtom. Prom. No. 6
Gennikh (Hennig), M. E. (1959)	"Stseplenie avtomobilnogo kolesa s deformiruemym gruntom" (Adhesion between automobile wheel and a soft ground) "Problemy povyshenya prokhodimosti..." Izdvo AttSSSR (quoted after Guskov, 1966)
Gilfillan, G. (1970)	"Tractor Behavior during Motion Uphill" J. Agric. Engrg Res. No. 3
Gill, W. R. & Vandenberg, G. E. (1967)	"Soil Dynamics in Tillage and Traction" USDA Ag. Handbook No. 316, Washington, D. C.
Gill, W. R. (1970)	"Report of Travel to the Soviet Union during Summar of 1970 under the MS-Soviet Exchange Agreement" NTML Auburn, Ala., USDA, Washington, D. C.
Ginsburg, B. Ya. (1968)	"O koeffitsiente stseplenya i buksovanya traktorov" (Coefficient of traction and the slip of tractors) Traktory i sielhozmashiny No. 9
Glagolev, N. I. & Poletayev, A. F. (1967)	"K voprosu obopredelenii koeffitisientov uprugnosti i vremeni relaksatsii pochvy" (Problem of determining coefficients of ...h and relaxation time of soil) Avtom. No. 3
Gorbachevskii, V. A. et al, (1969)	"Eksploatatsia mashin i mekhanizmov na lesozagotovkakh" (Usage of machinery in forest cultivation) Lesnaya Promyshlennost, Moscow

G

Gorbachevskii, V. A. (1970) "Rabota shin na lesotransporte" (Tire performance in forestry transportation) Lesnaya Promyshlennost, Moscow

Goriachkin, V. P. (1937) "Sobranie sochinenii" (Collection of works) Selhozgiz Vol. 2. Quoted from M G. Vasilevich (1959)

Gorin, G. S. (1970) "K dinamike gusennichnogo traktora" (Dynamics of a tracked tractor) Voprosy, Vol. XVIII, Minsk

Grecenko, A. (1963) "Kolove a pasove traktory" (Wheeled and Tracked Tractors) MZLVH, Prag.

Grecenko, A. (1967) "Binomic Slip-Thrust Equation...." Journal of Terramechanics, Vol. 4, No. 4

Grecenko, A. (1968) "Predicting Performance of Wheel Tractors in Combination with Implements" J. Agric. Engrg Res., No. 1

Grinchenko, I. V., et al (1967) "Wheeled Cross Country Vehicles" Translation by Techran Corp., Mashinostroyenye pp 1-234

Gruzdev, N. I. (1944) "Tanki-teoria" (Theory of Tanks) GIML, Moscow

Gross, W. A. & Elliott, A. D. (1946) "Traction as Influenced by Soils and Their Conditions", SAE Journal, Dec. Issue

Gudkov, A. H. (1968) "Teoreticheskie osnovy tekhnologicheskoi ustoichivosti rabochikh processov S-H mashin" (Theoretical principles of stability of working processes in agricultural machines) Zemledelcheskaya Mekhanika, Vol. XI

Gugushvilli, M. M. (1968) "K primenenii metoda dispersionnogo analiza... pri otsenkakh... S-H mashin" (Application of variance analysis... to evaluation... of agricultural machines) Zemledelcheskaya Mekhanika, Vol. X, Moscow

Gurkov, K. S. et al (1962) "Porgruzonnye mashiny dla sypuchikh i kuskovykh materialov" (Dirt moving equipment for granular and fragmented materials) GNT Izdat. Mashinostroennoi Literatury, Moscow

Guskov, V. V., Kuzmenko, V. A. and Badalov, M. Ya (1964) "Voprosy sel'skokohoziainoi mechaniki" (Problems of agricultural mechanics) Vol. 13 Uiozhai, Minsk

Guskov, V. V. (1966) "Optimalnye parametry sel'skohoziaistvennyh traktorov" (Optimum parameters of agricultural tractors) Mashinostroenye, Moscow

G

Guskov, V. V. (1967) "Weight Distribution for Tracklayers" Automotive Design Engineering, July Issue

Guskov, V. V. (1968) "Theoretical Principles Governing the Choice of Optimum Parameters of Track-Laying Tractors" Journal of Agricultural Engineering Research, No. 2

Guskov, V. V. (1968) "The Effect of Drawbar Pull on Rolling Resistance of Track-Laying Tractors" Journal of Terramechanics, Vol. 5, No. 4

Guskov, V. V. (1968 a) "Weight Distribution for Tracklayers" Automotive Design Engineering, July Issue

Guskov, V. V. (1968 b) "K voprosu vybora optimalnogo polozheniya tsentra tiazhesti gusienichnogo traktora" (Problem of selection of an optimum location of the center of gravity of a tracked tractor) Mechanizatsya i Elekrifikatsya Sielskogo Khozyaistva, 1st Ed.

Guskov, V. V. & Melnikov, I. S. (1969) "Vliyanie skorosti dvizhenya na tiagovyi'kpd' gusenichnogo traktora" (Effect of speed on coefficient of efficiency of a tracked tractor) Trudy, Vol. VI, Minsk

Guskov, V. V. (1969) Letter to the present writer, dated 10 November.

Gutyar, E. M. (1955) "Resistance of Wheels Moving in Ruts" Sielkhozmashina No. 2, English Translation NTML

H

Hadekel, R. (1952) "The Mechanical Characteristics of Pneumatic Tires" Ministry of Supply, S&T Memo No. 10/52, London

Haefeli, R., et al (1939) "Das Zeitprofil...der Schneedecke" (Time profile of snow cover) Bern

Headley, W. A. (1962) "Can We Put Numbers on Mobility?" GSE Vol. 4, No. 5. (Also see SAE 623F, 1963)

Hegedus, E. (1965) "Pressure Distribution under Rigid Wheels" Trans. of the ASAE, No. 2

H

Hendrick, J. G. (1969) "Recording Soil Penetrometer", J. Agric. Engrg Res. No. 2

Heyde, H. (1957) "Mechanik des Schleppers" Deutche Agrartechnik No. 1-4, E. Berlin, Also see the same author in Arhiv fuer Landtechnik Band 2, Heft 3, 1960

Housel, W. S. (1929) "A Practical Method for the Selection of Foundations Based on Fundamental Research in Soil Mechanics" Res. Bulletin No. 13, Univ. of Mich. Ann Arbor, Mich.

Hrobostov, S. H. and Harhurim, Sh. H. (1961) "O vliyanii pochvennykh uslovii na tiagovye kachestva traktorov" (Effect of soil characteristics upon pulling effort of tractors) Mekhanizatsya i Electrifikatsya Sotsialisticheskogo Selskogo Khoziaistva No. 1 quoted from Parfenov (1968)

I

Ignatenko, V. L and Klochkov, B. N. (1970) "Kharakter kolebanya pnevmopodveski autobusa LA 3-699A..." (Character of vibrations of pneumatic suspension of bus LA 3-699A) Avtom. Prom. No. 4

Indikt, E. A. et al (1968) "K voprosu o nadezhnosti avtomobilnykh konstruktsii" (Problem of reliability of automotive designs) Avtom. Prom. No. 11

Iofinov, A. P. and Taipov, N. N. (1969) "Dinamika processa vozhdenya S-H mashin" (Dynamics of motion of agricultural machines) Traktory i Selkhozmashiny, No. 6

Ishlinskii, A. Yu (1938) "Trenie kachenia" Prikladnaya matematika i mekhanika, Vol. 2, Moscow

Issledovanie rabochikh organov pochvoobrabatyvayushchykh mashin (1969) (Study of elements of soil-woring machines) Edited by A. I. Buyanov. ViskHOM, Moscow

Ivanov, N. H. (1950) "Osnovnye polozhenya mekhaniki gruntov opredelayushchie prokhodimost" (Principles of soil mechanics related to mobility) AHSSSR (quoted after Ageikin, 1970)

Ivanov, P. I. and Uvarov, V. N. (1967) "Priblizhennyi metod opredelenya vozmozhnykh srednikh skorostei...." (Approximate method of determining possible average speeds) Avtom. Prom. No. 11

J

Janosi, Z. (1959) "Prediction of WES Cone Index by Means of Stress-Strain Functions of Soils" Rep. No. 46 Land Locomotion Lab, OTAC, Warren, Mich.

Janosi, Z. and Hanamoto, B. (1961) "Analytical Determination of Drawbar Pull as a Function of Slip for Tracked Vehicles in Deformable Soils" Proc. First Int. Conf. on Terrain-Vehicle Systems, Edizioni Minerva Tecnica, Torino

Janosi, Z. (1961) "An Analysis of Pneumatic Tire Performance on Deformable Soils" First Int. Conf. on Terrain-Vehicle Systems, Edizioni Minerva Tecnica, Torino

Janosi, Z. and Hanamoto, B. (1961) "Analytical Determination of Drawbar Pull as a Function of Slip for Tracked Vehicles in Deformable Soil" Trans. First Int. Conf. on Terrain-Vehicle Systems, Edizioni Minerva Tecnica, Torino

Janosi, Z. (1963) "Performance Analysis of a Driven Non-Deflecting Tire in Soil" Rep. No. 8091, Land Locomotion Laboratory No. 84, ATAC, Warren, Mich.

K

Kananykhin, S. P. (1963) "Is ledovanie dopolnitelnykh poter' i iznosa shin" (Study of additional losses and wear of tires) Avtom. Prom. No. 4

Karelin, V. N. (1964) "Issledovanie raboty dwizhitelei sedelnogo avtomobilya-tyagacha na snezhnoi tseline" (Study of work of a tractor on snow covered field) Avtom. Prom. No. 7

Katsygin, V. V. and Azlamova, E. N. (1960) "Pribory i prisposoblenya dla issledovanii fizyko-mekhanicheskikh svoistv pochv" (Instrumentation for study of physico-mechanical properties of soils) Voprosy zemledelcheskoi mehaniki, Vol. V, Minsk

Katsygin, V. V. (1962) "O zakonomernosti soprotivlenya pochv szhatiu" (Law of soil resistance to shear) Sielhozgiz BSSR, Minsk

Katsygin, V. V. (1963) "Voprosy tehnologii mehanizovannogo selskokhozyaistvennogo proizvodstva" (Technilogical problems of mechanized agricultural production), BSSR, Selhozgiz, Minsk

K

Katsygin, V. V. (1963 a)	Trudy, Vol. 1, TsNIIMESH, pp 65-71, Minsk
Katsygin, V. V. (1964)	Chapter I, Voprosy Selskokhozyaistvennoi Mekhaniki, Urozhi, Minsk
Katsygin, V. V. (1964)	"Osnovy teorii vybora optimalnykh parametrov mobilnykh selskokhoziaistvennykh mashin i orudii" (Principles of theory of selecting optimum parameters of mobile agricultural machines and tools) Voprosy selskokhoziaistvennoi mekhaniki, Vol. XIII, Chapter I
Katsygin, V. V. (1964 a)	"Nekotorye voprosy deformatsii pochv" Sielhozgiz, BSSR, Minsk
Katsygin, V. V. and Guskov, V. V. (1968)	"The Basis of Tractor Performance Theory", Journal of Terramechanics, Vol. 5, No. 3
Kav'yarov, I. S. and Pozin, B. M. (1967)	"Osnovnye korrelatsionnye zavisimosti mezhdu parametrami gusenichnykh traktorov i ikh agregatov" (Principal correlational relationship between parameters of tracked tractors and their aggregate machinery) Traktory i Sel'khozmashiny, No. 8
Kedrov, B. M. (1963)	"Voprosy Filozofii" (Questions of Philosophy) No. 5, 1960. Reprinted in Soviet Review, Spring Issue.
Khachatryan, H. A. (1965)	"Rabota S-H agregatov naisilno pereschennoi mestnosti" (Agricultural aggregates in a very rugged terrain) AN ARM SSR, Erevan
Khlebnikov, A. M. and Osipyan, A. W. (1963)	"K piatidesiatiletiyu Tsentralnogo Nauchno-Issledovatelskogo Avtomobilnogo i Avtomotornogo Instituta" (Fiftieth Anniversary of the Central R&D Institute for Automobiles and Automotive Engines) Avtom. Prom., No. 11
Klazhinskii, Ya. A. et al (1967)	"Osnovy automatiki i automatizatsii stroitelstva automobilnykh dorog" (Principles of automation of construction of motorways) Transport, Moscow
Klenin, N. I., et al (1970)	"Selskokhozyaistvennye mashiny" (Agricultural Machines) Kolos, Moscow
Klochkov, B. I. (1961)	"Buksovanie vedushchikh koles automobilya na dorogah s myaghkim pokrytiem" (Slip of driving wheels of an automobile on soft road cover) Avtom. Prom. No. 7

Klochkov, Yu. M. (1967) "Vliyanie skorosti dvizhenya gusenichnogo traktora... po snezhnoi tseline, na soprotivlenie kachenyu" (Speed effect of motion of a tracked tractor in snow, upon motion resistance) Traktory i Selkhozmashiny, No. 7

Klychkov, P.D. (1961) "Ob opredelenii optimal'noi udelnoi moshchnosti proektiruemogo avtopoezda" (Determination of optimum specific power of a motor vehicle, prior to design stage) Avtom. Prom. No. 11

Kneschke, A. (1957) "Rollerfeibung auf spurbildener Fahrbahn" (Rolling friction on deformable road) Ingenieur Archiv, Vol. 25, No. 4

Knight, S.J. (1956) "A Summary of Trafficability Studies through 1955", T.M. No. 3-240 14 Supplement WES, Vicksburg, Miss.

Knight, S.J. and Freitag, R.D. (1964) "Comments on Mobility Research" Waterways Experiment Station, SAE 782B, New York, N.Y.

Knoroz, V.I. (1960) "Robota avto mobilnoi shiny" (Work of a pneumatic tire) Gospolitizdat quoted from "Voprosy..." Vol. 13, (1964)

Knoroz, V.I. et al (1968) "Vliyanie soprotivleniya kacheniyu shin na raskhod topliva avtomobilei" (Effect of tire motion resistance upon fuel economy of motor vehicles) Avtom. Prom. No. 3

Kochetkov, N.W. (1968) "Analiz... eksperimentalnogo issledovanya emergetiki i dinamiki S-H transportnykh sredstv s kolesnymi dvizhitelami" (Analysis... of experimental studies in power and dynamics of agricultural transportation based on wheeled prime movers) Zemledelcheskaya Mekhanika, Vol. XI., Moscow

Kogler, F. (1933) Discussion re: "Soil Mechanics Research" by Gilboy, Proc. Am. Soc. of Civil Engrs., Vol. 59

Kocheulov, V.P. and Korsak, V.P. (1970) "Kritika i bibliografya" (Critique and bibliography) Review of the book on "Introduction to Terrain-Vehicle Systems" by M. G. Bekker, Avtom. Prom. No. 11

Kodenko, M.N. et al (1969) "Avtomatizatsia traktornykh agregatov" (Automation of tractor-soil working machine aggregates) Mashins stroenye, Moscow

Kolobov, G.G. (1960) "Experimental Investigation of Specific Contact Pressure Distribution under Pneumatic Tires in Soil" English Translation, Traktryi Sielhozmashing, No. 12

K

Kolobov, G. G. (1970) — "Tipazh sovetskikh traktorov" (Classification of types of Soviet tractors) Traktory Sel'khozmash. No. 4

Kol'tsov, et al (1969) — "K postroieniyu modeli kachenya elastichnogo kolesa pri bystro menayushchikhsya nagruzkakh" (Models of rolling elastic wheel at rapidly changing loads) Mashinostroyenie No. 2

Komandi, G. (1968) — "The Determination of Soil Properties from Slip-Pull Curves", Journal of Terramechanics, Vol. 5, No. 2

Komarov, M. S. and Zatserkovnyi, I. G. (1962) — "Issledovanie svobodnykh kolebanii avtobusa s podveskoi peremennoi zheskosti" (Study of bus vibrations with suspension of varying elasticity) Avtom. Prom., No. 3

Konev, Yu. A. (1970) — 'Matematicheskii podhod k izucheniyu vliyaniya psikhofiziologii cheloveka na upravlenie avtomobilen" (Mathematical Study of the effect of psycho-phisiological structure of man upon car driving) Avtom. Prom., No. 5

Korchunov, S. S. (1948) — "Nesushchaia sposobnost i deformatsya nizinnoi torfyannoi zemli" (Bearing capacity and deformation of low land turf layers) VNIITP, Gosenergoizdat, Moscow (Quoted after Guskov, 1966)

Korotonoshko, H. I. (1968) — "Puti razvitiya konstruktsii polnoprivodnykh avtomobilei vysokoi prokhodimosti" (Ways of developing all wheel drive high mobility motor vehicles) Avtom. Prom. No. 11

Korsun, N. A. and Levitanus, A. D. (1970) — "Statisticheskii analiz osnovnykh parametrov traktorov obshchego naznacheniya" (Statistical analysis of principal parameters of tractors for general use) Trakt. i Sel'khozmash. No. 6

Kosharnyi, N. F. (1966) — "Issledovanie soprotivleniya perekatyvaniyu shiny nizkogo davleniya po gruntu" (Study of motion resistance of a low pressure pneumatic tire) Inst. Mekh & Elektrifik Sielhoz. USSR Vypusk 5, pp 128, 141

Kragelskii, I. V. (1945) — Abstracts of Russian work (on snow), Stefansson Library

Kragelskii, I. V. (1945) — "Physico mechanical properties of snow..." Abstract prepared in English for the Stefansson Library in 1948, New York

Kragelskii, I. V., et al (1948) — Abstracts of Russian Work (on snow), Stefannsson Library

Krasilnikov, V. Ye. (1966)	"Kachenie kolesa po deformiruemoi poverkhnosti s bokovym uvodom" (Wheel rolling with a cornering drift on deformable soil) Traktory i Siel'khozmash. No. 6
Kristi, M. K. (1937)	"Tanki" (Tanks), VAMM, Moscow
Kristi, M. K. (1938) Editor	"Avtotraktoryi spravochnik" (Auto-tractor handbook) Vol. IV., ONTI, Moscow
Krivshin, A. P. et al (1969)	"Povyshenie proizvoditelnosti zemleroino transportnykh mashin" (Increase of productivity of soil-working transport equipment) MADI, Moscow
Krizhivitskii, A. A. (1950)	"Issledovanie snegohodnyh mashin i tehnicheskie trebovania k nim" (Study of snow going machines and their technical requirements) Akd. SC., SSSR, quoted from Klochkov (1970)
Krutikov, A. (1951)	"Teoria, konstruktsya i raschot selskokhoziaistvennykh mashin" (Theory, construction and evaluation of agricultural machinery) Mashgiz quoted from Bernacki (1963)
Kudinov, R. A. (1964)	"Traction and Coefficient of Efficiency of a Wheeled Tractor in Turn" (Translation by Univ. of Detroit Translation Ctr.) Traktory i Sel'khozmashiny No. 10
Kurzel, I. A. (1962)	"Roschet raskhoda topliva i skorosti avtomobilya s gidromekhanicheskoi transmissiei" (Calculation of speed and fuel consumption of an automobile with a hydrodynamic transmission for a variable regime of work) Avtom. Prom. No. 3
Kuzmenko, V. A. (1960)	"Ustanovka dla izuchenya tiagovo-stsepnkh svoistv koles) (Equipment for the study of tractive properties of wheels) Voprosy Zemledelcheskoi Mekhaniki, Vol. V., Chapter II.
Kuzmenko, V. A. (1963)	"Experimentalno teoreticheskie osnovanya vybora optimalnykh parametrov kolesnogo traktora" (Experimental and theoretical principles of parameter optimization of wheeled tractors) Trudy, Vol. I, Minsk
Kuznietsov, A. A. (1962)	"Ob opredelenii udelnyh soprotivlenii pochvy po znachenyam tverdosti" (Determination of specific resistance of soil from the viewpoint of hardness) Traktory i Sielkhozmashiny, No. 2

K

Kuznietsov, E. S. (1968) "Obobshchayushchie pokazateli ekspluatatsionnoi nadèzhnosti avtomobilei" (Generalized indices of operational reliability of motor vehicles) Avtom. Prom. No. 3

L

Lebedev, P. A. and Sidorov, N. G. (1965) "K issledovanyu vzaimodeistvya gusenichnogo traktora s gruntom pri povorote" (Investigation of relationship between a tracked tractor and the ground, in turning) Traktorii Sel'khozmashiny No. 3

Lehr, E. (1934) "Die Schwingunstechnik" (Technology of vibrations) Springer, Berlin

Letoshnev, M. N. (1936) "Teoria i proisvodstvo sielskokhoziainikh mashin" (Theory and development of agricultural machines) Vol. 3, Kolesnye povozki, Moscow

Lurie, A. B. (1963) "Vvedenie v staticheskuyu dinamiku navesnykh S-H aggregatov" (Intorudction to the statistical dynamics of suspended agricultural machine aggregates) Trudy, Vol. I., Minsk

Lurie, A. B. et al (1969) "K metodike statisticheskoi otsenki soprotivlenya pochvy pri pakhote" (Statistical method for evaluation of ground resistance in tillage) Zapiski Leningradskogo S-H Instituta, Vol. 138, Leningrad

Lurie, A. B. and Nagorskii, I. S. (1969) "Modelirovanie na AMM S-H agregata kak dvukhmernoi dinamicheskoi sistemy" (Modelling of an agricultural aggregate as a two-dimensional system by means of AMM) Zapiski Leningradskogo S-H Instituta, Vol. 138, Leningrad

Lvov, A. A. (1969) "K voprosu otsenki prokhodimosti traktorov bezrazmernymi parametrami" (Problem of assessment of tractor mobility by means of dimensionless parameters) Trudy, Vol. VII, Minsk

Lvov, E. D. (1952 a) "Teoria Traktora" (Tractor Theory) Mashgiz, Moscow

Lvov, E. D. (1960) "Teoria Traktora" (Theory of a Tractor) Mashgiz, quoted after Guskov (1966)

L

Lysov, A. M. (1970) "Postroyenie tyagovoi kharakteristiki traktora s primeneniem AVM" (Determination of tractional characteristics of a tractor by means of a computer) Traktory i Sel'khozmash. No. 10

Lysov, M. I. (1961) "Metodika opredelenya manevrennosti avtomobilya na povorotakh" (Methodology of determing vehicle maneuverability, in turns) Avtom. Prom. No. 8

M

Makarets, I. K. et al (1967) "Vliyanie kolesnyh traktorov na fizicheskie svoistva pochvy" (Effect of wheel tractors upon physical soil properties) Traktory i Siel'khozmashiny, No. 3

Malyshev, A. A. (1958) "Kachenie kolesa s pnevmaticheskoi shinoi po deformiruyushcheisya gruntovoi poverhnosti s obrazovanyem kolei" (Pneumatic tire in a rut) Trudy MHDI 22 Ed. Avtotransizdat

Margolin, Sh. F. (1961) See Matsepuro & Katsygin (1961)

Markaryan, S. I. and Khoetsyan, S. H. (1969) "Nauchnye osnovy vybora i eksploatatsii sistemy mashin... s primeneniem elektronno-vychyslennykh mashin" (Scientific principles of selection and use of a machine system... with the help of electronic computers) Trudy, Arm NIIMESH, Vol. VII, Erevan

Martens, L., Editor (after 1948) Mashinostroenie, Vol. II (Machine Design) Moscow

Matsepuro, M. Ye. and Guskov, V. V. (1961) Chapter I, "Voprosy zemledelcheskoi mechaniki", (Problems of Terramechanics), Minsk

Matsepuro, M. Ye. and Runtso, A. A. (1961) Chapter III, "Voprosy zemledel'cheskoi mekhaniki" (Problems of Terramechanics) Jrozhav, Minsk

Matsepuro, M. Ye. and Selitskii, S. S. (1961) Chapter II, Voprosy zemledelcheskoi mekhaniki (Problems of Terramechanics), Vol. VI Acad. Agr. SC., Minsk

Matsepuro, M. Ye. and Yanushkevich, B. N. (1961) "Rabota khodovykh apparatov traktorov i sel'skokhoziainykh mashin na deformiruemykh gruntakh" (Work of running gears of tractors and agricultural machines on soft ground) Chapter VI., Voprosy..." Minsk

Matsepuro, M. Ye. and Hao-Sin-Fan (1962)	"Voprosy zemledelcheskoi mekhaniki", Vol. VIII, Chapter 5
Matsepuro, M. Ye. and Katsygin, V. V. (1963)	"Protsessy deformatsii, peremeshchenya i rezanya pochvogruntov" (Processes of deformation, displacement and cutting of soils), Selhozgiz, BSSR, Minsk
Matsepuro, V. Ye. (1969)	"Modelirovani S-H sred i materialov vyazko-plasticheskim telom" (Modeling agricultural products and materials by means of a visco-plastic mass), Trudy, Vol. VIII, Minsk
Mayer, R. (1910 ?)	"Handbuch der Ingenieur-Wissenschaften" 3rd Ed., Vol 1, p. 17-18, quoted from Bernstein (1913)
McKenzie, R. D. et al (1967)	"Computerized Evaluation of Driver-Vehicle-Terrain System" SAE 670168, New York, N. Y.
McKibben, E . G. and Davidson, J. B. (1939)	Agricultural Engineering, Vol. 20, No. 12
McKibben, E. G. and Davidson, J. B. (1940)	Agricultural Engineering, Vol. 21, Nos. 1,2, 3,4,7
McKibben, E. G. and Green, R. L. (1940)	Agricultural Engineering, Vol. 21, No. 5
McKibben, E. G. and Hull, D. O. (1940)	Agricultural Engineering, Vol. 21, No. 6
McLeod, H. E., et al (1966)	"Draft Power Efficiency and Soil Compaction of... Tires", Transactions of the ASAE, pp 41-44
McLeod, H. E. et al (1966)	"Draft, Power Efficiency and Soil Compaction Characteristics of Single, Dual and Low Pressure Tires" Trans. ASAE, pp 41-44
McRae, J. L. (1967)	"Theory of a Powered Wheel in Soil" Journal of Terramechanics, Vol. 4, No. 3
Mechanical Engineering (1970)	p. 19, June Issue, ASME, New York, N. Y.
Mechanics of Soil-Vehicle Systems (1961)	Proc. Symposium on Terrain-Vehicle Systems, Edizioni Minerva Tecnica, Torino
Medvedev, M. I. (1934)	"Kinematika gusenichnykh tsepi" (Kinematics of tracks) ONTI, Moscow

M

Medvedkov, W. I. and Yar'kov, W. A. (1968) — "Primenenie ETVM dla rascheta skorostnogo rezhima dvizheniya avtomobilya" (Application of computers to the evaluation of speed regime of an automobile), Avtom. Prom. No. 3

"Mekhanizatsia i Elektrifikatsia Selskogo Khoziaistva" (1968) — M. S. H., BSSR, Minsk

Melnikov, E. S. (1966) — "Vliyanie skorosti deformatsii na velichinu napryazhenia szhatya v torfyano-bolotnykh pochvah" (Deformation speed effect upon shear of turf-mud type of soils), Mekh. i Elekt. Sots, Selsk. Khoz. No. 8

Melnikov, Ye. S. (1969) — "Vliyanie skorosti na velichinu kasatelnoi sily tyagi gusenichnogo traktora" (Speed effect upon traction of a tracked tractor) Trudy, Vol. VII, Minsk

Meyerhof, G. G. (1961) — "Bearing Capacity of Floating Ice Sheets" Am. Soc. of Civil Engrs. Proc., Vol. 86

Meyerhof, G. G. (1962) — "Load Carrying Capacity of Concrete Pavements", Am. Soc. of Civil Engrs. Proc. Vol. 88

Mihatoiu, I. (1970) — "Contributii la studiul presiunii pe sol. . . " (A Contribution to the Study of Ground Pressure. . .) Studii si cercetari de mecanica agricola, Vol. IV., No. 1

Mitschke, M. (1962) — "Influence of Road and Vehicle Dimensions on the Amplitude of Body Motions and Dynamic Wheel Loads" SAE Transactions, Vol. 70

Morin, M. A. (1840-41) — "Memoir sur le tirage des voitures. . . . . " (Memorandum on vehicle hauling), Comptes Rendus de l'Acad. des Sciences, Vol. 10 & 11

N

Nadezhdin, G. W. (1964) — "K voprosu vliyanya shiriny oboda shiny na gruzopodyemnost shiny" (About the effect of width of tire profile upon its load carrying capacity) Avtom. Prom. No. 8

Nafikov, M. Z. and Poliakov, I. S. (1968) — "Raschet soprotivlenia dvizheniiu traktora" (Calculation of tractor motion resistance) Traktory i Siel' hozmash. No. 1

Nagorskii, I. S. (1967)	"Primenenie elektronoi modeliruyushchei Ustanovki MNB-1 dla reshenya zadach S-H mekhaniki" (Application of the electronic computer MNB-1 to the solution of problems of agricultural mechanics) Voprosy S-H Mekhaniki, Vol. XVII, Yurozhai, Minsk
Nagorskii, I. S. and Chumak, V. K. (1967)	"Opredelenie statisticheskikh kharakteristik sluchainykh processov s pomoshchyu analogovoi vychislennoi mashiny" (Determination of statistical properties of random processes by means of an analog computer) Trudy, Vol. V Minsk
Nagorskii, I. S. and Bokhan, N. I. (1969)	"Opredelenie parametrov sistemy automaticheskogo upravlenya khodom rabochykh organov... elektronnoi modeli" (Determination of system parameters by means of electronic models for automatic control of working elements...) "Trudy", Vol VII, Minsk
Naidenov, B. F. et al., (1969)	"Razvitie tekhnikoekomicheskikh issledovanii v NAMI" (Development of technical-economic studies at NAMI) (Avtom. Prom., No. 11
Nakaya, U. et al. (1934-36)	"Physical Investigation of Snow..." J. Faculty of Science, Hokkaido Univ.
"Nauchnye osnovy povyshenya rabochikh skorostei mashinno-traktornykh agregatov"	Collective work published by the Min. of Agric. USSR., Kolos, Moscow
Nikitin, S. A. (1967)	"Izmenenya v strukture, organizatsii i spetsializatsii avtomobilnogo ptoizvodstva" (Changes in the structure, organization and specialization of automotive production) Avtom. Prom. No. 10
Nofinov, A. P. & Tailov, N. N. (1969)	"Dinamika protsessa vozhdeniya SH mashin" (Dynamics of towing agricultural machines) Traktory i sel'khozmashiny, No. 6
Novichikhin, V. A. (1968)	"O zakonomernostyakh soprotivlenya pochvy vdavlivanyu" (On rules of soil resistance in penetration) Zemledelcheskaya Mekhanika, Vol. X

N

Novichikhin V. A. (1968) "O zakonomernostyakh soprotivlenya pochvy vdavlivanyu" (Rules of resistance in soil penetration). Zemledelcheskaya Mekhanika, Vol. X, Moscow

O

Oganesyan, A. P. (1949) "Effect of Mechanical Composition of Soil on Draft Resistance" Akad. Nauk, SSSR Moskov (Ousted after Guskov).

Omelianov, A. E. (1948) "O primenenii pnevmaticheskikh koles na selskokhoziainikh mashinakh" (Application of pneumatic tires to agricultural machinery) Sielkhozmashiny No. 5

Opeiko, F. A. (1961) "Nekotorye voprosy teorii gusennichnogo dvizhitela" (Some problems of a tracked prime mover), Chapter V "Voprosy"..., Minsk

Opeiko, F. A. (1962) Naivygodneishee raspredelenie davlenii na grunt pri razlichnykh polozheniakh tsentra davleniya u gusennichnogo traktora" (Optimum ground pressure centers of a tracked tractor" "Voprosy..." Chapter IV, Vol. VIII, Minsk

Opeiko, F. A. (1970) "Issledovane povorota gusenichnogo tractora" (Analysis of turning a tracked tractor) "Voprosy..." Vol. XVIII, Minsk

ORG (1947) Report No. 352, "Measurement of the Shear Strength of Soils in the Field", Min. of Supply London

Ostrovtsev, N. A. (1969) "Samokhodnye katki na pnevmaticheskikh shinakh" (Automovers on pneumatic tires) Mashinostroyenie, Moscow

Ostrovtsev, A. N. & Derbaremdiker, A. D. (1970) "O probleme optimizatsii vzaimodeistvya cheloveka i avtotransportnoi tekhniki" (Problem of optimization of man - auto transport technology system) Avtom. Prom. No. 7

P

Palovnev, V. I. (1960) "Method of Determining Basic Parameters of a Bulldozer Blade" Stroitelnoye i Dorozhnoe Mashinostroenye No. 1, English translation by NTHL.

P

Parfenov, A. P. (1968) — "O nominalnom tiagovom usilii SH traktora" (On nominal drawbar pull of an agricultural tractor) Traktory i Sel'hozmashiny No. 2

Parkhilovskii, I. G. (1961) — "Spektralnaya plotnost raspredelenya nerovnostei mikroprofilya dorog i kolebanya avtomobilya" (Spectral density of roughness distribution of road microprofile and the vibrations of a vehicle) Avtom. Prom. No. 10

Parkhilovskii, I. G. & Zaitseva, N. F. (1964) — "Statisticheskoe issledovanie kolebanii avtomobilya na elektronnoi modeliruyushchei nashine" (Statistical study of vehicle vibrations) Autom. Prom. No. 1

Parkhilovskii, I. G. (1966) — "Ob opredelenii eksploatatsionnykh trebovanii k plavnosti khoda avtomobilei" (Determination of utilitarian requirements of automotive ride comfort) Avtom. Prom. No. 1

Petrov, E. V. (1966) — "Metod opredelenya utochnennykh znachenii koeffitsienta vnutrennikh poter' massivnykh rezinovykh shin" (Method of an accurate determination of coefficients of internal losses in solid Rubber tires) Avtom. Prom. No. 10

Petrushov, V. A. (1967) — "O dynamicheskom faktore avtomobilya s uchetom svoistv kolesnogo dvizhitela" (On the dynamic factor of an automobile, considering properties of wheel drive) Avtom. Prom. No. 5

Pevzner, Ya M. & Tikhonov, A. A. (1964) — "Issledovanie statisticheskikh svoistv mikroprofilya osnovnykh tipov avtomobilnykh dorog" (Study of statistical properties of the microprofile of roads) Avtom. Prom. No. 1

Pigulevskii, I. H. (1929) — "Otsenka vozdeistvya na pochvu pochvozatsepnykh konstruktsii traktorov na osnove izuchenia struktury pochvy i ee mekhanicheskikh svoistv" (Evaluation of the effect of soil gripping tractor devices, upon soil, on the basis of cognizance of soil structure and its mechanical properties) VKKIT; quoted from Briukhoviets (1957)

Pigulevskii, I. H. (1936) — "Osnovy i metody izuchenya fiziko-mechanicheskih svoistv pochvy" (Principles and methods of defining physico-mechanical properties of the ground). Quoted from Zelenin (1950)

Pigulevskii, I. H. (1936 a) — "Theoria, konstruktsiia i proizvodstvo selskohoziaistviennyh mashin" (Theory, construction and production of agricultural machines) Vol. 2, Sielhozgiz

P

Pochekhonov Yu. V. (1969) "Nauchnyi Kollektiv" (Scientific Collective) Voprosy Filozofii No. 10, 1969. Reprinted by Sovjetwissenchaft, Wissenschaftliche Beitrage No. 3, Berlin

Podskrebko, M. D. (1967) "Influence of Speed of Deformation on Resistance of Soil" Translation by NTML. Proc. Chelyabinskii Institut Mekhanizatsii i Elektrifikatsii Sel'skogo Khozyaistva., No. 17

Podskrebko, M. D. (1967 a) "Determination of Poisson Ratio and Modulus of Deformation of Soils;" as above; No. 26

Pogosbekov, M. I. (1961) "K opredelniyu k. p. d. vedushchego kolesa avtomobilya" (Determination of the coefficient of efficiency of the driving wheel of an automobile) Avtom. Prom. No. 9

Poletaev, A. F. & G. G. Kolobov (1959) "O gruzopodemnosti pnevmaticheskikh traktornykh shin" (Load carrying capacity of pneumatic tractor tires) Traktory i Siel'khozmashiny, No. 1

Poliakov, I. S. & Nafikov, M. Z. (1969) "Determination of coefficient of traction and resistance to movement by soil parameters" Engl. translation by NTML. Mehanizatsya i Elect. Sots. Sielsk Khoz. No. 11

Polyakov, I. S. & Nafikov, M. Z. (1969 a) "Determining Terrain Trafficability" Translation J-6905 by J. Public Service, Military Herald No. 6

Popov, D. A., et al. (1970) "Metodika ispytanii traktorov na plavnost' khoda" (Method of the investigation of tractor stability) Traktory i Sel'khozmash. No. 5

Powell, C. J. & Green, A. G. (1965) "Performance of Soils under Tire Loads", WES TR 3-666

Pradko, F. (1962) "Vehicle Dynamics" SAE SP 240, New York, N. Y.

Prandtl, L. (1920) "Uber die Harte plastischer Korper." Nachr. kgl. Ges. Wiss. Göttingen (Math-Phys Klasse)

"Pravda" (1971) "Pervaya peredvizhnaya laboratorya na lune" (First mobile laboratory, on the moon), No. 40, 9 February issue

Prikhodko, L. S. & Schupak, P. L. (1970) "K metodike analiza komponentov soprotivlenii deistvuyushchikh na traktor (Methodology of analysis of the elements of resistances acting upon a tractor) Traktory i sel'khozmash. No. 5

<u>Proc. First Int. Conf. on Terrain-Vehicle Systems (1961)</u> Torino-St. Vincent, Edizioni Minerva Tecnica, Torino

P

Proc. Second Int. Conf. on Terrain-Vehicle Systems (1966)	Quebec, Que., Univ. of Toronto Press, Toronto, Ont.
Proc. Third Int. Conf. on Terrain-Vehicle Systems (1969)	Essen, ISTVS, Hoboken, N.J.
Proctor, R.R. (1933)	"Soil Compaction" Eng. News Record, Vol. 59
Puzyakov, N.A. (1931)	"Issledovanie formy... dla opredelenya nesushchei sposobnosti deformatsii gruntov" (Study of plate forms for determination of the bearing capacity and deformation of the ground) LNITSH, Leningrad

R

Rashevsky, N. (1959-1964)	"Bulletin of Mathematical Biophysics" Vols. 21-26, Univ. of Chicago Press, Chicago
Razorenov, V.F.	"Penetratsionnye ispytanya gruntov" (Penetration studies of soils) Izd. Literat. po Stroitelstvu, Moskow
Reece, A.R. (1965)	"Principles of Soil-Vehicle Mechanics", Inst. of Mechanical Engineers, London
Revuta, I.B. & Rode, A.A. (1969)	"Metodicheskoe rukovodstvo po izuchenyu pochvennoi struktury" (Methodological guide in a study of soil structure) Kolos, Leningrad
Reznikov, A.S. (1968)	"Razvitie komponovok sovremennykh gorodskikh avtobusov" (Development of configuration of modern city buses) Avtom. Prom. No. 11
Richter, G.D. (1945)	"Snow Cover, its Formation and Properties," English translation, USSR Akad. of Science, Moscow
Rokas, S.I. (1960)	"Metokika otsenki prohodimosti samokhodnykh kolesnykh mashin" Stroitelnoe i Dorozhnoe Mashinostroenie, No. 5
	See also: Avtomobilnaya Promyshlennost No. 5, 1963, as reported by ATZ No. 9, 1969
Rokas, S.I. (1963)	"Zavisimost soprotivlenya kacheniu avtomobilya ZIL-157 ot sostoyanya gruntov" (Relationship between motion resistance of ZIL-187 and ground consistency) Avtom. Prom. No. 5
Rokas, S.I. (1965)	"Determination of Basic Properties of Soils for Evaluation of Vehicle Traction" Avtom. Prom. No. 1

R

Rotenberg, R. V. (1963) "Elektronno-vychislitelnye mashiny i tekhnicheskii progress v avtomobilstroenii" (Computers and technological progress in automotive technology) Avtom. Prom. No. 4

Rotenberg, R. V. (1963) "Razvitie teorii avtomobilei v uslovyakh primeneniya EVM" (Development of automobile theory with the help of electronic calculating machines) Avtom. Prom. No. 9

Rukavichnikov, S. W. (1957) "Koefficient sceplenya koefficient soprotvlenya dwizhenyu gusenichnogo dvizhitelia snegokhodnykh mashin" (Coefficents of adhesion and motion of tracked snow-going prime movers), Trudy GPI, Vol III, Gorkii. Quoted from Klochkov (1670)

Rukavichnikov, S. W. (1957) "Koefficient stseplenya i koefficient soprotivlenya dwizheniyii gusiennichnogo dwizhitela snegokhodnykh mashin" (Coefficients and adhesion and motion resistance of tracked vehicles, in Snow) Trudy GPI im. A. A. Zhdanova, Vol. III, Gorkii. Quoted after Kolochkov (1967)

Rumyantsev, V. A. (1969) "Novye koustruktsii traktornykh ekskavatorov" (New designs in tractor-excacator equipment) Mashinostroenye, Moscow

Runenkov, A. V. (1968) "O metodakh uskorennykh poligonnykh ispytanii agregatov avtomobilei na nadezhost'i dolgovechnost" (Methods of accelerated proving ground testing of automobile aggregates for reliability and endurance) Avtom. Prom. No. 10

S

Saakyan, D. N. (1969) "Sistema pokazatelei kompleksnoi otsenki mobilnykh agregatov" (System of Indices for composite evaluation of mobile aggregate machines) Mashinostroyenie, Moscow

Saakyan, S. S. (1953) "Slip of a Driven Wheel on a Plastic Medium" Mekh. Elektr. Sotj. Selsk. Khoz. No. 4, English translation by NTML

Saakyan, S. S. (1954) "Zavisimost soprotivlenya pochvy vdavlivanyu ot diametra shtampa" (Dependence of soil resistance in penetration, from plate diameter) Selkhozmashina, No. 5

Saakyan, S. S. (1959) "Vzaimodeistvie vedomogo kolesa i pochvy" (Interrelation between Driven Wheel and Soil), MSX Arm SSR, Erevan

SAE (1945) SAE Tractor War Emergency Committee, Rep No. 4

Sakharov, A. (1970) "Scientists Lament" Newsweek, Feb. 1, p. 32

Samilkin, V.D. (1959) "Opredelenie soprotivlenya perekatyvanyu kolesnogo traktora" (Determination of motion resistance of a wheeled tractor) Traktory i Sielikhozmashiny, No. 5

Saukyan, D.N. (1968) "Teoria rascheta stoimosti S-H mashinnoi raboty" (Theory of value assessment in agricultural mechanical work) Zemledelcheskaya Mekhanika, Vol. X, Moscow

Savinykh, V.N. (1969) "Issledovanie yavlenya relaksatsii v pochvo-gruntakh" (Study of the relaxation phenomena in soils) Trudy, Vol. VII, Minsk

Schiffman, R.L. (1961) "Analysis of the Displacements of the Ground Surface Due to a Moving Vehicle" Proc. 1st Int. Conf. on Terrain-Vehicle Systems, Edizione Minerva Technica, Torino

Schüring, D. (1968) "The Wheel on Soft and Rigid Ground" First Int. Conf. on Veh. Mech., Wayne State Univ., Detroit, Mich.

Schüring, D. (1968 a) "Zur Theorie des Geländerades" (On the Theory of an Off-the-Road Wheel) Forschung im Ingenieurwesen VDI Dusseldorf Vol. 34, Nr 6

Sedov, L.I. (1970) "Mekhanika sploshnoi sredy" (Continuum mechanics) Nauka, Moscow

Selitskii & Matsepuro, M.E. (1961) Chapter II, "Voprosy Zemledelcheskoi Mehaniki" (Problems of Terramechanics) Yrozhai, Minsk

Semenov, W.M. & Armaderov, R.G. (1961) "Soprotivlenye dwihenyu avtomobilya ZIL-150 na kolesah z arochnymi i standartnymi shinami" (Motion resistance of ZIL-150 equipped with "rolligon" and standard tires) Avtom. Prom. No. 10

Sergeev, V., et al. (1970) "Optimizatsya eksploatatsionnykh parametrov pakhotnykh agregatov" (Optimisation of performance parameters of ploughing aggregates) Vestnik Selskokhoziyastvennoi Nauki No. 3

Sevrov, K.P. (1970) "Avtogreidery, konstruktsya i raschet" (Graders - design and engineering calculations) Mashinostroenie, Moscow

Shavlcv, A. I. (1963) "Ispytanie raboty pnevmaticheskikh vedomykh koles na rykhlykh gruntakh" (Study of pneumatic driven wheels on loose soils) Traktory i Sielhozmashiny No. 4

Shipilevskii, G. B. (1970) "Povyshenie kachestva avtomaticheskogo vozhdenya gusenichnogo traktora" (Increase of quality of automated motion of a tracked tractor) Traktory i Sel'khozmash. No. 11

Shchupak, P. L. & Makarov, N. M. (1964) "Proving Ground for Determination of Drawbar Pull of Tractors" English Translation by The Univ. of Detroit Translation Center, Traktory i Sielhozmashiny No. 1(

Silukov, Yu.D. (1962) "Dvizhenye avtomobilya MAZ-501 na arochnykh shinah po snegu" (Mobility of MAZ-501 with "rolligon" tires in snow) Avtom. Prom. No. 1

Sineokov, G. N. (1965) "Design of Tillage Machinery" Mashine Design Publ. House Moscow, Chapter 2. English translation by NTML

Sinitsyn, I. F. (1967) "Traktornoie i selskokhozyaistvennoe mashinostroenie k 50-letnemu yubileyu velikogo oktyabrya" (Tractor and agricultural machinery design, on the fiftyeth anniversary of the Great October) Traktory i Sel'khoz-mashiny, No. 10

Sirotkin, A., et al. (1968) "O matematicheskom i naturnom issledovanii gidromekhanicheskoi peredachi abtomobilya" (Mathematical and experimental study of a hydro-mechanic transmission of an automobile) Avtom. Prom. No. 9

Sitkei, G. (1966) "Sinkage and Rolling Resistance of Wheels on Loose Sand" Proc. Second Int. Conf. on Terrain-Vehicle Systems, Quebec City, Que., Univ. of Toronto Press, Toronto

Sitkei, G. (1967) "Soil Mechanics Problems of Agricultural Machinery" Akad. of Science, Budapest

Skotnikov, V. A. (1963) "Off-the-Road Mobility of Tracked Tractors" Traktory i Siehozmashiny No. 1, English translation available

Skotnikov, V. A., et al. (1969) "Mashiny dlya stroitelstva i soderzhanya osushchitelnykh kanalov" (Equipment for constructing and maintainance of drainage canals) Mashinostroenie, Moscow

Skryabin, A. K. (1969) "Optimalnoe programirovanie... etc" (Optimum programing...) Zemledelcheskaya Mekhanika, Vol. XI, Moscow

Skundin, G. I. (1969) "Mekhanicheskie transmissii kolesnykh i guesenichnykh traktorov" (Mechanical transmissions of wheeled and tracked tractors) Mashinostroenyey, Moscow

Skundin, G. I. & Dobrokhlebov, A. P. (1970) "Issledovanie nagruzhennosti transmissii kolesnykh i gusenichnykh traktorov" (Study of transmission loads of tracked and wheeled tractors) Traktory i Sel'khozmash. No. 3

Slivinskii, V. I. & Titov, A. V. (1970) "O differentsialnykh svyazakh motor-koles elektricheskikh transmissii avtomobilei i avtopoezdov" (On differential ties between the motor and the wheels for electric transmissions of motor vehicles) Avtom. Prom. No. 3

Smirnov, G. A., et al. (1964) "Vybor programmy dlya ispytanya glavnykh peredach... na stendakh s programnym upravleniem" (Program selection for main transmission testing on stands with programmed input) Avtom. Prom. No. 4

Smirnov, G. A. & Lelikov, O. P. (1967) "Vliyanie skhemy silovogo privoda na tyagovo-stsepnye kachestva avtomobilei tipa 8x8" (Effect of drive line scheme upon pull-traction properties of an 8x8 vehicle) Avtom. Prom. No. 6

Smirnov, G. A. & Izvozchikov, V. S. (1969) "Vliyanie skhemy silovogo privoda na poteriv transmissii avtomobilei tipa 8x8" (Effect of power train type upon transmission losses of 8x8) Mashinostroyenie No. 2

Smirnov, G. A. & Lelikov, O. P. (1970) "Raspredelenie krutyashchykh momentov...pri dvizhenii po deformiruemym gruntam" (Distribution of torque... during the driving on soft soils) Avtom. Prom. No. 4

Sofyaan, A. P. (1960) "The Problem of Adhesion of Tractor Tracks to the Ground" Translation IPST Cat No. s 728, 729, 731, 734, 736. Office Tech. Serv. U.S. Dept. of Commerce, Washington 25, D.C.

Söhne, W. (1956) "Einige Grundlagen für eine Landtechnische Bodenmechanik" Grundl. d. Landtechn. Heft 7

Söhne, W. (1958) "Fundamentals of Pressure Distribution and Soil Compaction under Traction Tires" English translation in Agr. Engrng., May issue

Sokolovski, V. V. (1942) "Statika sypuchei sredy" Gosizdat, Moscow

Soltynski, A. (1962) "Neiktóre zagadnienia ruchu ciagnika kotowego (Some Problems of Driving a Wheeled Tractor) Technika Samochodowa, No. 1

Soltynski, A. (1966) 'Mechanika ukladu pojazd-teren" (The Mechanics of a terrain-vehicle system) Ministry of Nat'l Defense, Warsaw

S

Sorokin, E. M. (1970) "Pakhotnye traktory, ikh konstruirovanye osobennosti i napravlenie razvitiya" (Agricultural tractors, their design features and direction of development) Traktiy i Sel'khozmash. No. 4

Stolbov, L. M. & Kopelevich, L. M. (1969) "Vliyanie skorosti dvizheniya na pokazateli raboty gusienichnogo traktora" (Effect of speed on efficiency of a tracked tractor) Traktory i Sel'hozmashiny No. 7

Strokin N. I. (1968) "O povyshenii roli nauchnykh issledovanii v razvitii automobilnoi promyshlennosti" (On increasing the role of scientific studies in the development of automobile industry) Avtom. Prom. No. 11

Strokov, V. L. (1964) "Energy Expenditure for Locomotion of Driven Pneumatic Tires in Soil" English Translation by NTML, Doklady Timiryazev Selhoz Akad No. 96

Strokov, V. L. (1968) "K voprosu povysheniya prokhodimosti kolesnykh mashin" (Contribution to the Problem of Mobility Increase of Wheeled Vehicles) Zemledelcheskay a mekhanika, Vol. X

Svirshchevskii, B. S. (1958) "Ekspluatatsia mashinno-traktornogo parka" (use of machine-tractor materiel) Selkhozgiz. Quoted from Ginsburg (1968)

T

Taylor, D. E. (1948) "Fundamentals of Soil Mechanics," John Wiley & Sons

Tchaikovskii, I. P. (1967) "Issledovanie protsessa stabilizatsii upravlyaemykh koles s primeneniem analogovoi EVM." (Study of stabilization of steering wheels by means of an analog computer) Avtom. Prom. No. 6

Telegin, V. M. (1970) "Ob otsenke upravlaemosti avtomobilya" (Evaluation of vehicle controllability) Avtom. Prom. No. 9

"Teoria Avtomobilya" (1942) Chapter VI, pp 27-30

Terzaghi, K. (1943) "Theoretical Soil Mechanics." Wiley & Sons, New York, N. Y.

Tolpekin, S. (1969) "The Mechanization of Soviet Agriculture: the Economic Effect." Progress Publishers, Moscow

Torchinskii, W. T. (1962) "Issledovanie soprotivlenya dvizhenyu na nerovnykh dorogakh" (Investigation of motion resistance on rough roads) Avtom. Prom. No. 3

Traktory i Siel'khozmashiny (1968) No. 1, p. 16

Traktory i Siel'khozmashiny (1969) "Sobranie sochinenii akademika V. P. Goriachkina" Goriachkin, Editorial.

T

Trepenenkov, I. I. (1963) — "Exploatatsionnye pkazateli sh traktorov" (Exponents of agricultural tractor performance) Mashgiz. Quoted from Ginsburg (1968)

Troitskaya, M. N. (1947) — 'Zavisimost mezhdu siloi i deformatsiei kak osnovy rascheta prochnosti gruntov v dorozhnyh konstruktsiah" (Relationship between force and deformation as a basis for evaluation of strength of ground in highway construction) DorNII Ed., VII M.

'Trudy institut a fiziki zemli (1953) — No. 2 Moscow

"Trudy" (1963) — Vol. 1 TsNIMESH, Minsk

"Trudy" (1969) — TsNiimesh, Works of the Central Scientific Res. Inst. for Mechanization and Electrification of Agriculture, Vol. VI, Izdatelstvo Urozhai, Minsk

Tsimberov, P. I. (1958) — "Otsenka plavnosti khoda avtomobilya s uchetom vliyanii kolebanii na cheloveka metodom elektronnonaturnogo modelirovaniya" (Evaluation of automobile stability considering its effect upon man, by means of electronic vibration modelling) Avtom. Prom. No. 4

Tsukerberg (Zukerberg), S. M. and R. K. Gordon (1965) — "Opredelenie eksploatatsionnykh kachestv avtomobiinykh shin metodom modelirovanya" (Determination of utilitarian qualities of automobile tires by means of modelling" Avtom. Prom. No. 11

Tsymbal, A. G. *1958) — 'A Rotational Penetrometer" English translation by NTML Bulletin No. 1, All Russian Res. Inst. of Mech. & Electrific. of Agric. Zernovoi Rostov Region

Turetskii R. L. (1969) — 'Vliyanie sostoyanya grunta i rezhimov trenya na koefitsient trenya" (Effect of ground state and of the type of friction, on the coefficient of friction) "Trudy" Vol. VII, Minsk

Turetskii, R. L. (1970) — 'Nauchnye osnovy povyshenya proizvoditelnosti zemleroino-meliorativnykh mashin" (Scientific principles of productivity increase of soil-moving and ground reclamation equipment) "Trudy" Vol. XVIII Minsk

U

Uffelman, F. L. (1961) — "The Performance of Rigid Cylindrical Wheels in Clay Soils" Proc. 1st Int. Conf. on Terrain-Vehicle Systems Edizioni Minerva Tecnica, Torino

Ul'yanov N. A. (1962) — "Osnovy teorii i rascheta kolesnogo dvizhitela" (Theory and calculation of a wheeled prime mover) Mashgiz, Moscow

U

Ul'yanov N. A. (1962) 'Osnovy teorii i rascheta kolesnogo dvizhitela zemlcroinykh mashin" (Principles of theory and engineering calculations for a wheeled prime mover of soil-moving machines) Mashgiz. Moscow

UL'yanov, F. G. (1964) "Povyshenie prokhodimosti i tyagovykh svoistv kolesnykh traktorov na pnevmaticheskikh shinakh" (Improvement of mobility and traction of tractors equipped with pneumatic tires) Mashinostroyenie, Moscow

Ul'yanov, N. A. (1969) 'Teoria samokhodnykh kolesnykh zemleroino-transportnykh mashin" (Theory of wheeled motor vehicles in transport and earth working), Mashinostroyenie, Moscow

V

Valge, A. M. and Krasnov V. P. (1969) 'K metodike profillirovanya poverkhnosti polya" (Method of measuring ground surface profile) Zapiski Leningradskogo S-H Instituta Vol. 138 Leningrad

Vasilenko, P. M. (1950) "Theory of a Rolling Wheel in Ruts, " (Quoted from an English translation of Gutyar's (1955) paper.)

Vasilenko, P. M. (1950) 'K teorii kachenya kolesa so sledom" (Theory on wheel rolling in a rut) Selhozmashiny No. 9. Quoted from Andreev (1956)

Vasilenko, P. M. (1967) 'O perekhodnykh protsessakh v mashinno-traktornykh agregatakh" (Transient phenomena in tractor-machine aggregates) Zemledelcheskaya Mekhanika, Vol. VII, Moscow

Vasilenko, P. M. (1968) " O primenenii metoda optimalnykh reshenii pri razrabotke problem selskokhozyaistvennoi tekhniki" (Application of the method of optimum solution to the problems of agricultural technology) Zemledelcheskaya Mekhanika, Vol. X

Vasilenko P. M. (1968) 'Sovremennye matematicheskie metody i ikh primenenie v zemledelcheskoi mekhanikie" (Modern mathematical methods and their application to agricultural mechanics) Zemledelcheskaya Mekhanika, Vol. X, Moscow

Vasilenko P. M. (1968a) 'Mathematicheskie metody optimalnykh reshenii" (Mathematical methods of optimization) Zemledelcheskaya Mekhanika, Vol. XI

Vasilevich, M. G. (1959) "Vneshnii energeticheskii balans navesnogo traktornogo agregata" (Internal energy balance of a tractor-machine aggregate) Traktory i Sielhozmas. No. 1

V

Vasiliev, A. V., et al. (1969)	Vliyanie konstruktivnykh parametrov gusienichnoge traktora na ego tyagovostseplnye svoistva (Effect of design of a tracked tractor upon its tractive properties) Mashinostroenie, Moscow
Velev, N.N. (1967)	'Traction calculation of agricultural tractors" Translation NTML, Traktory i Sel'khozmash. No. 7
Vernikov, I.S. (1940)	'Speed of Movement and Sinkage in Soil of Rolling Wheels" Sel'skohhoz-Mashina No. 8/9, English Translation by NTML
Vetrov, Ya. A. (1957)	"The Problem of Determining Cutting Resistance of Soil" Stroitelnoye, Dorozhnoye Mashinostroyenye, No. 1
Vinogradov, V.I. (1968)	"Investigation of the Dynamic Strength of Soil" English translation by NTML. Mech. i Elektrif. Sots. Sel. Khoz. No. 6
Vlasov, M.A. & Kuperman, A.L. (1961)	'Rezultaty ispytanii arochnykh shin na standartnykh gruzovykh avtomobilyakh ZIL i GAS" (Results of testing "rolligon" type tires with standard ZIL and GAZ trucks) Avtom. Prom. No. 8
Voleidt, N.A. (1952)	'Gruzopodiemnost mashin v selskom khoziaystve" (Load capacity of machines in agriculture) Lecture VIM. Quoted from M.G. Vasilevich (1959)
'Voprosy Selskokhoziaystvennoi Mekhaniki"(1964)	(Problems of Agricultural Mechanics) Urozhai, Vol. XIII, Minsk
"Voprosy..." (1964)	Vol. XIV, pp 213-226
'Voprosy Zemledelcheskoi Mechaniki"(1960)	(Problems of Agricultural Mechanics) Vol. III, Minsk
"Voprosy Zemledelcheskoi Mehaniki" (1961)	(Problems of Agricultural Mechanics), Vol. VI, Minsk
Vysotskii, A.A. (1965)	'New Integrating Instruments for the Determination of the Physical-Mechanical Properties of Soils" Traktory i Sel'khozmash. No. 1

W

Weiss, S.J. (1952)	'Use of the Soil Truss...." U.S. Naval Civil Engrs Res. & Eval. Lab., Port Hueneme, Calif., TN-075
WES (1965)	'Deflection of Moving Tires" TRR No. 3-516 Rep 3, Vicksburg, Miss.
Windish, E.J. & Yong, R.N. (1970)	"The Determination of Soil Strain Rate Behavior beneath a Moving Wheel" Journal of Terramechanics, Vol. 7, No. 1
Wintergerst, E. (1940)	'Die Technische Physik des Krafcwagens" (Technical Physics of an Automobile) J. Springer, Berlin

W

Wislicki, A. (1969) "Współzależność parametrów lemiesza i zespołu jezdnego spycharki oraz warunków gruntowych" (Relationship between the parameters of a bulldozer blade, the tractor running gear and soil conditions). Instytut Organizacji i Mechanizacji Budownictwa No. 582, Warsaw

Wong, J. Y. & Reece A. R. (1966) "Soil Failure Beneath Rigid Wheels" Proc. Sec. Int. Conf. on Terrain-Vehicle Syst., Quebec City, Que., Univ. of Toronto Press, Toronto

XYZ

Yankin, V. M. (1968) "Resistance to Forward Movement of a Track-Laying Tractor... on Snow..." English translation by Gaylord Publications. Tractory i Siel'khozmashiny No. 9

Yatsenko, N. N. & Prutchikov, A. K. (1963) "Issledovanie podvesok avtomobilei vysokoi prokhodimosti" (Study of suspensions of cross country vehicles) Avtom. Prom. No. 3

Yong, R. M. (1969) "Energy Dissipation and Drawbar Pull, Prediction in Soil Wheel Interaction," Proc. 3rd Int. Conference of the Int. Soc. for Terrain-Vehicle Systems, Essen.

Yuvenatiev, Y. N. (1939) "Aerosanye" (Propeller Sleds), Moscow

Zaichik M. I. et. al., (1937) "Tiagovye mashiny i podvizhnoi sostav lesovoznykh dorog" (Tractors and carriers for forest roads) Lesnaya Promyshlennost, Moscow

Zakin Ya. H. (1967) "Prikladnaya teoria dvizhenya autopoezda" (Applied theory of motion of a motorvehicle) transport, Moscow

Zaks, M. N. (1964) "Poperchnaya ustoichivost' samosvalov pri bokovom oprokidyvanii gruza" (Lateral stability of dump trucks for lateral discharge of dirt) Avtom. Prom. No. 12

Zaleski, S. K. (1956) "Corrections for Reading Soil Penetrometers" Translation NTML, Selhozmashiny No. 8

Zapolski, B. V. (1960) "Gidravlicheskaya apparatura dla issledovanya stsepnykh kachestv trakov gusenichnogo dvizhitia" (Hydraulic apparatus for the study of traction of tracked prime-movers" Voprosy Zemledel'cheskoi Mechanliki, Vol. V. Chap. II.

Zaslavski, B. I. (1932) "Kratkii kurs raschota tankov" (Short course of calculating tank performance and design parameters) NKTM (?) Moscow

Z

Zelenin, A.N. (1950) "Fizicheskie osnovy rezania gruntov" (Physical principles of ground cutting) Institute of Mines, Acad. Sc. SSSR, Moscow & Leningrad

Zavalishin F.S. (1968) 'O kriteryakh primenyaemykh pri proiektirovanii proizvodsvennykh protsessov" (Criteria for planning productive processes) Zemledelcheskaya Mekhanika, Vol. XI

Zelenin, A.N. (1968) 'Osnovy rozrushanya gruntov mekhanicheskimi sposobami," 2nd Ed (Principles of ground loosening with mechanical means) Mashinostoenye, Moscow

Zelenin, A.N. et al., (1969) "Laboratoryni praktikum po rezanii gruntow" (Laboratory guide to ground cutting), Vysshaya Shkola (textbook publisher) Moscow

Zheligovski, V.A. (1937) 'Spravochnik inzhenera-mekhanika..." (Handbook of a mechanical engineer) Selhozgiz. (Quoted after Gutyar (1955)

Zheligovski, V.A. (1950) "Ishodnie soobrazhenya dla izuchenya snizhenya tyagovykh soprotivlenii pri zamene stalnih koles pnevmaticheskimi (New contribution to studies on reducing draft by substituting steel wheels with pneumatics). Doklady VASKHNIL 2nd Ed. Quoted from Andreev (1956)

Zheligovskii, V.A. (1960) "Elementy teorii pochvoobrabatyvayushchikh mashin i mekhanicheskoi tekhnologii SH materialov (Elements of a theory of soil-working machinery and mechanical technology of agricultural materials) Tibilisskii SHI

Zheligovskii, V.A., Ed (1967) Zemledel'cheskaya mekhanika" (Mechanics of soil works) Vol. VII, Lenin Akad. Agric. Sc., Moscow

Zheligovskii, V.A., Ed (1968) "Zemledel'cheskaya mekhanika" (Mechanics of soil work), Vol. XI, Mashinostroyenie, Moscow

Zhilin, A.P. & Labodaev, V.D. (1967) 'K voprosu izuchenya energoemkosti perevozok traktornymi transportnymi agregatami" (Exploring energy requirements in transportation which utilizes tractor-trailer aggregates 'Trudy" Vol. V

Zhilin, A.P. 'K opredelenyu optimalnykh parametrov traktornykh transportnykh agregatov" (Determination of optimum parameters of tractor-trailer transporters) TsNIIMESH, Minsk

Zhukov, A.V. (1970) 'O viliyanii nerovnostei dorog na prodolnoe vzaimodeistvie zvenev avtopoezda" (Effect of road roughness on longitudinal interaction of elements of an articulated vehicle) Avtom. Prom. No. 9

Zimielev, G.V. (1957) "Teoria Abtomobilia" (Automobile Theory) VIMOS, Moscow

SYMBOLS

A	area cm^2
A'	soil deformation work (kgm)
A_o	coefficient of the maximum shearing stress of turf, moss soil in Korchunov's equation (kg/cm^2)
B_o	coefficient of the maximum bearing stress of turf, moss soil in Korchunov's equation (kg/cm)
B'	width as specified (cm)
C	Rokas penetrometer torque constant
C_1	Omelianov's tire coefficient in rut making
C_2	Omelianov's tire carcass stiffness coefficient
C_3	Ageikin's coefficient of tire structure
D	wheel diameter (cm)
D_r	"relative" tire diameter in Knoroz equation (cm)
E_o, E_1, E_2 etc.	energy (kg cm)
E	Young modulus (kg/cm^2)
F	size of the loading or ground contact area (cm^2)
G	modulus of rigidity (kg/cm^2)
H	soil thrust (kg)
H_o	track tension (kg)

K	Janosi's coefficient of slip (1/cm or 1/in.)
K_1	Bekker's coefficient of slip (1/cm or 1/in.)
K_2	Bekker's coefficient of slip
K_{NP}	Nafikov's and Polyakov's exponent of soil deformation corrected for the test plate size (1/cm)
K_o	Opeiko's modulus of horizontal ground strength (kg/cm^2)
L	length as specified (cm)
MC	moisture content (%)
MC_H	moisture content as the higher limit of plasticity index (%)
MC_L	moisture content at the lower limit of plasticity index (%)
N	number as specified
N_{PL}	plasticity number
P	force (kg)
R	motion resistance (kg)
S	shearing force (kg)
S'	ground contact area produced by the tips of the spuds (cm^2)
S_m	integrated index of road roughness (cm/km)
S_o	Skotnikov's unit load (kg/cm^2)
T	torque (kg cm)

SYMBOLS (Cont'd)

U	circumference of the loading area (cm)
V	volume of deformed soil (cm^3)
W	load (kg)
W_1	weight of unsprung mass (kg)

* * * *

a	acceleration (cm/sec^2)
a'	Letoshnev-Bernstein's coefficient of loading, perimeter effect ($kg/cm^{3.5}$)
a''	Letoshnev-Bernstein's coefficient of loading, surface effect ($kg/cm^{4.5}$)
a_1	Bernstein's coefficient of soil deformation for a rigid wheel ($kg/cm^{1.5}$)
a_2	Bernstein's coefficient of soil deformation for a rigid wheel ($kg/cm^{2.5}$)
b	width of the ground contact area (cm)
b_m	coefficient of turf cover-strength, related to shear and compression (cm)
c	Coulombian coefficient of soil cohesion (kg/cm^2)
c_1, c_3	Pokrovskii's empirical coefficients of soil shear (kg)
c_2	Pokrovskii's empirical coefficient of soil shear (1/cm)
c_4	Pokrovskii's empirical coefficient of soil shear (1/cm)
c_t	coefficient of tire carcass stiffness (kg/cm^3)
d	plate diameter (cm)
f_A	unit motion resistance (R/W)
f_s	safety factor

h	height (cm)
h_g	ground clearance (cm)
i_o	slip
i_s	slope
j, j_o	length of horizontal soil shear (cm)
k	modulus of soil penetration obtained in accordance with Bernstein-Letoshnev theory but without specifying the plate size and form (kg/cm^3)
$k'k''k'''$	Bernstein's original coefficients of equations fitting the load-deformation curve (kg/cm^2, kg/cm^3, kg/cm^4 respectively)
k_B	Bernstein's modulus of soil deformation (kg/cm$^{2.5}$)
k'_B	Bernstein-Letoshnev modulus of soil deformation for rigid wheel (kg/cm^{n+2})
k_c	Bekker's "cohesive modulus of soil deformation" (kg/cm^{n+1} or lb/in.$^{n+1}$)
k_{co}	modulus of soil deformation for a cone (kg/in.$^{n+2}$)
k_G	Gutyar's "elasto-plastic" modulus of soil deformation (kg/cm^3)
k'_G	Gutyar's "plastic" modulus of soil deformation (kg/cm^3)
k_K	Knoroz' bearing capacity coefficient of soil for pneumatic tires (kg/cm^2)
k_{KA}	Katsygin's coefficient of soil deformation (kg/cm^3)
k'_{KA}	Katsygin's coefficient of soil deformation corrected for plate size (kg/cm^3)
k''_{KA}	Katsygin's coefficient of soil deformation in Bernsteinian equation involving dimensionless sinkage z for plate diameter D (kg/cm^2)
k'''_{KA}	Katsygin's coefficient of soil deformation in Bernsteinian's equation involving dimensionless sinkage z, for plate width b (kg/cm^2)
k_{KL}	Korchunov's coefficient of soil deformation at lower limit of plasticity index
k_V	Klochkov's coefficient of snow penetration load at a given speed
k_{KO}	Korchunov's coefficient of turf deformation (cm)

SYMBOLS (Cont'd)

k_L	Letoshnev's modulus of soil deformation (kg/cm^3)
k_{NP}	Nafikov and Poliakov's modulus of soil deformation (kg/cm^3)
k'_{NP}	Nafikov and Poliakov's modulus of soil deformation for the test plate (kg/cm^3)
k_o	Opeiko's coefficient of horizontal shear
k_{OM}	Omelianov's coefficient of soil deformation for a tire (kg/cm^3)
k_{PT}	Compounded exponent of soil deformation combined with Pokrovskii-Troitskaya soil values
k_S	Saakyan's modulus of soil deformation (kg/cm^2)
k_{SK}	Skotnikov's modulus of soil deformation, corrected by plate size (kg/cm^3)
k_t	Modulus of turf deformation (kg/cm^{n+2})
k_T	Troitskaya's coefficient of soil strength
k_V	Vernikov's modulus of soil deformation reflecting speed effect measured in density change (kg/cm^3)
k'_V	Saakyan's coefficient of wheel slip in a slip-sinkage function ($1/cm^n$)
k_Z	Ageikin's modulus of soil deformation (kg/cm^2)
k_φ	Bekker's "frictional" modulus of soil deformation (kg/cm^{n+2} or $lb/in.^{n+2}$)
k_δ	Coefficient of motion resistance due to the snow filling the path of the road wheels
k_τ	Katsygin's coefficient of shear (cm)
l	track pitch (cm)
m_1	Force coefficient of critical load for the wheel bulldozing turf (kg)
m_2	Unit load coefficient of critical load for the wheel bulldozing turf (kg/cm^2)
m_z	Ageikin's coefficient of stress attenuation in soil
m	Melnikov's empirical coefficient of speed effect upon soil penetration ($kg\ sec^2/cm^4$)
n	Letoshnev's generalized exponent of sinkage
n_v	Saakyan's exponent of wheel slip in a slip-sinkage function

SYMBOLS (Cont'd)

p	ground pressure (kg/cm^2)
p_c	Troitskaiya's maximum bearing strength of soil (kg/cm^2)
p_{ca}	Tire carcass stiffness pressure (kg/cm^2)
p_i	Tire inflation pressure (kg/cm^2)
p_q	"average" tire ground pressure (kg/cm^2)
p_{KA}	Katsygin's ultimate bearing capacity of soil (kg/cm^2)
p_{KO}	Korchunov's maximum bearing capacity of turf soil (kg/cm^2)
p_{OL}	Korchunov's bearing capacity of turf soil at the lower limit of plasticity index (kg/cm^2)
p_{ov}	Klochkov's resistance to penetration with speed v (kg/cm^2)
p_s	ground bearing capacity (kg/cm^2)
r	radius (cm)
r'	radius of curvature of the side walls of the tire under load (cm)
s	distance (cm)
s_t	track link length (cm)
t	time (sec)
t_{ff}	time of "free fall" sinkage of the loading area (sec)
u	Vernikov's coefficient of soil compressibility
z	sinkage (cm)
z_d	dynamic sinkage at given vehicle speed (cm)

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SYMBOLS (Cont'd)

$\alpha, \alpha_1, \alpha_2 \ldots$	angles or coefficients as specified
$\beta, \beta_1, \beta_2 \ldots$	angles or coefficients as specified
γ	soil density (kg/cm^3)
γ_1, γ_2	angles or coefficients as specified
Δ	tire deflection (cm)
δ	stress (kg/cm^2)
ϵ	Andreev's coefficient of wheel skid $\epsilon = i_o/(i_o-1)$
ζ, ζ', ζ_1 etc.	coefficients or ratios as specified
ζ_t	coefficient of non-uniformity of track pressure distribution
η	Andreev's coefficient of wheel slip: $\eta = i_o/1-i_o)$
η_s	Skotnikov's empirical soil coefficient
η_T	coefficient of efficiency (output/input ratio)
$\varkappa$	Lvov's coefficient of load distribution on tire contact area

λ	ratio of sinkage to the thickness of deformed soil layer
λ_o	Lvov's coefficient of diameter deformation of a tire
μ	viscosity (kg sec/cm^2)
μ_A	Ageikin's coefficient of internal soil friction (tan φ)
μ_a	coefficient of "adhesion" between the ground and the vehicle
μ_f	coefficient of friction
μ_{KA}	Katsygin's coefficient of compound friction
μ_m	Katsygin's coefficient of friction "in shear"
μ_o	coefficient of friction between metal and soil
μ'_o	Katsygin's coefficient of friction "at rest"
μ_r	coefficient of friction between rubber and soil
μ'_T	coefficient of soil thrust
ρ_1	Birulya's coefficient of energy loss due to road roughness
ρ_2	transfer coefficient of road roughness
σ_t	coefficient of form of the body interacting with soil
τ	soil shear stress (kg/cm^2)
τ_{av}	shear stress per unit of perimeter length (kg/cm)
τ_o	Troitskaya's maximum shear strength of soil (kg/cm^2)

φ	Coulombian angle of friction (deg)
φ_s	angle of soil-wheel rim slip ($\tan^{-1} \mu_0$)
$\Psi_1 (\tau)$	Rokas soil index of shear strength
$\Psi_2 (p)$	Rokas soil index of bearing capacity

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Γ	Kuznetsov's ground hardness (kg/cm^2)
Π	Rokas index of mobility